BTO RESEARCH REPORT 788

Review of methods used to calculate scale of artificial nesting structures proposed as a compensation measure for Kittiwake mortality at offshore wind farms

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BTO Birds Science People

ACKNOWLEDGEMENTS: This report was supported with funds from Defra and the Collaboration on Offshore Wind Strategic Compensation. We thank Andrew Harwood, Richard Berridge and Martin Kerby (Natural England) for managing the project and providing technical steer, and the members of the Offshore Artificial Nest Structure Implementation Group for commenting on an earlier draft. This project is part of the Natural England / BTO Research Partnership providing the evidence needed to support nature's recovery and people's experience of the natural world.

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BTO Research Report 788 – Revision (October 2025)

Natural England supports the government's targets for green energy and have published our Approach to Offshore Wind where we strive for 'Thriving marine and coastal nature alongside low impact offshore wind energy, tackling both climate and biodiversity emergencies'.

We have now reached a stage where adverse effects on several seabird Special Protection Areas (SPAs) cannot be ruled out due to the size of the predicted impacts of multiple offshore wind farms on seabird features, resulting in a need for compensation. However, there is significant uncertainty regarding the appropriate scale of compensation for a given impact, and several proposed methods for calculating the requirements yield different results. To address this, Natural England, on behalf of the Collaboration in Offshore Wind Strategic Compensation (COWSC) group, commissioned the British Trust for Ornithology to carry out an independent, evidence-based review of existing methods and consider possible alternatives. This review focuses on the use of Artificial Nest Structure (ANS) compensation measures for Black-legged kittiwake (*Rissa tridactyla*), whilst briefly considering applications for other species and measures. This evidence will be used to inform future guidance on suitable approaches for calculating the scale of seabird compensatory measures.

Natural England commission a range of reports from external contractors to provide evidence and advice to assist us in delivering our duties. The views in this report are those of the authors and do not necessarily represent those of Natural England.

BTO, The Nunnery, Thetford, Norfolk IP24 2PU
Tel: +44 (0)1842 750050 Email: info@bto.org
Registered Charity Number 216652 (England & Wales), SC039193 (Scotland).

ISBN 978-1-912642-75-5

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Glossary of terms

Artificial nest structure (ANS): Artificial structure providing habitat (i.e. nest spaces) for breeding birds, constructed (in this context) as a compensation measure for bird mortality at offshore wind farms.

Compensation magnitude: The ratio of the compensation target and compensation population (i.e. compensation population divided by compensation target).

Compensation measure: An activity or management intervention intended to offset the impacts to protected seabirds at offshore wind farms.

Compensation population: Size of the population (number of breeding pairs) required at the artificial nest structure to produce the number of recruits (i.e. first-time breeding birds) equal to the compensation target to offset the predicted mortality.

Compensation ratio: A multiplier sometimes applied to the calculated compensation population size to account for uncertainties in the methods or demographic parameters used to estimate the compensation population or to account for uncertainty in the success of the implementation of the compensation measure.

Compensation target: Estimated annual figure of bird mortality at a proposed offshore wind farm. In the context of this report, the compensation target exclusively relates to Kittiwake mortality at the wind farm as a result of turbine collision, determined through Collision Risk Modelling. It does not account for Kittiwake mortality that may occur elsewhere as a result of the wind farm, such as through displacement or reduced survival rate. However, incorporation of mortality arising from these avenues could theoretically be incorporated by increasing the compensation target.

Counterfactual population: Breeding birds that are assumed to exist and produce recruits at locations other than the artificial nest structure, if the artificial nest structure theoretically did not exist.

Dispersal rate: The breeding dispersal or adult dispersal rates represent the proportion of breeding age individuals that migrate to breed at other colonies each year. Natal dispersal or juvenile dispersal rates represent the proportion of individuals in a cohort that recruit into a breeding colony separate from their birth colony. Dispersal rates are generally considered to be complementary behaviours to philopatry or site faithfulness of known individuals, not measures of net emigration between individual colonies within the wider metapopulation.

Recruit: First-time breeding bird. A philopatric recruit is an individual returning to their colony of birth as a breeder.

Sabbatical bird: A bird that has previously bred, but skips breeding in a specific breeding year.

Sink population: A single population within a metapopulation in which the death rate is higher than the birth rate. The population may be sustained by immigration from other populations.

Source population: A single population within a metapopulation in which the birth rate is higher than the death rate.

Timescale for payback: The amount of time (in years) until the number of accumulated recruits produced at an ANS exceeds the accumulated mortality.

List of acronyms

Acronym	Meaning
AA	Appropriate Assessment
AEoI	Adverse Effects on Integrity
ANS	Artificial Nest Structure
AOE	Alde-Ore Estuary
AON	Apparently occupied nests
BTO	British Trust for Ornithology
COWSC	Collaboration on Offshore Wind Strategic Compensation
DEP	Dudgeon Offshore Wind Farm Extension Project
FFC	Flamborough and Filey Coast
HRA	Habitat Regulation Assessment
IROPI	Imperative Reasons of Overriding Public Interest
JNCC	Joint Nature Conservation Committee
KCSG	Kittiwake Compensation Steering Group
NNC	North Norfolk Coast
ORJIP	Offshore Renewables Joint Industry Programme
OTE	Outer Thames Estuary
OWF	Offshore wind farm
OWSMRF	Offshore Wind Strategic Monitoring and Research Forum
RSPB	The Royal Society for the Protection of Birds
SAC	Special Area of Conservation
SEP	Sheringham Shoal Offshore Wind Farm Extension Project
SMP	Seabird Monitoring Programme
SPA	Special Protection Area
TCE	The Crown Estate
UK	United Kingdom

Executive summary

1. Artificial Nest Structures (ANSs) have been approved as strategic compensation measures following derogation cases required to enable the consent of several offshore wind farms due to concerns about negative impacts on seabird features of designated Special Protection Areas (SPAs). However, there is stakeholder disagreement regarding the efficacy of such compensation measures and the methods used to calculate their required scale, i.e. the number of breeding Kittiwake pairs needed to occupy the site to produce the number of new breeding birds required to compensate the predicted mortality impact.

2. In this report, we reviewed the suitability of methods used to calculate the scale of ANSs provided as compensation measures for Kittiwake mortality at offshore wind farms in English waters, due to turbine collision only.

3. We found that methods used were inconsistent across the wind farm developments. In particular:

   i) Some developments followed a 'new colony' approach, where all breeding birds produced at the ANS counted towards the compensation target. This approach is based on the assumption that birds recruiting to the ANS would not have bred elsewhere in the metapopulation, which in turn implies the existence of a non-negligeable pool of adult non-breeders. Others followed a 'surplus bird' approach, where only birds in excess of either breeding birds that would have been produced elsewhere in the absence of the ANS (assuming a higher breeding productivity at the ANS), or those needed to replace mortality at the ANS, counted towards the compensation target. One development (Hornsea 3) used a hybrid of these approaches, where a 'surplus' was not calculated against a counterfactual, but only birds expected to disperse to other sites counted towards the compensation target, albeit under the assumption of unrealistically high dispersal rates. Another development (the Sheringham Shoal and Dudgeon Offshore Wind Farm Extension Projects) used a different approach based on the relocation of birds nesting in suboptimal sites in an existing ANS to newly constructed sites in the same ANS of higher breeding productivity.

   ii) Values of demographic parameters used in the compensation calculations differed across the developments.

   iii) Only three developments modelled estimated timescales for achieving the compensation targets. Estimated timescales are highly sensitive to assumptions around the colonisation rate, breeding productivity and initial size of the ANS population. Empirical data to assess these assumptions are generally lacking.

4. ANSs further need to: i) compensate for turbine collision mortality of birds at the ANS, ii) replace birds lost at the ANS due to natural mortality, and iii) account for the fact that only a portion of birds produced will disperse to the existing wider metapopulation. Although the methods employed by the reviewed wind farm developments accounted for some of these elements, none accounted for all three.

5. Existing data regarding Kittiwake metapopulation dynamics and variability in demographic rates are limited. However, the calculated scale of compensation is highly sensitive to the choice of demographic rates regardless of the methodology. The lack of empirical data on ANS performance thus leads to large uncertainty over the optimality of methods used for calculating compensation requirements, and ultimately leads to uncertainty about the efficacy of ANSs as a compensation measure overall.

6. There is also limited information regarding additional factors potentially impacting Kittiwake metapopulation dynamics, such as spatial and temporal trends in demographic parameters, colonisation and population growth rates, metapopulation dynamics, and density dependence. Consequently, these factors were not able to be considered (or fully considered) by the offshore wind developers during the calculation of compensation scale. However, these factors are the subject of ongoing research that could facilitate inclusion of additional information into future calculations of compensation scale.

7. The combined total number of nest spaces provided by existing and proposed ANSs is significant in the context of the most recent population estimates. Provision of ANSs at this scale may have measurable impacts on regional metapopulation dynamics and this needs to be accounted for in the monitoring of both ANSs and naturally nesting populations.

8. The extent of monitoring undertaken at operational ANSs will largely determine the form and feasibility of future modelling attempts aiming to evaluate their efficacy as a compensation measure and the overall impact on the existing Kittiwake metapopulation.

9. We briefly review additional compensation approaches for species other than Kittiwake and the considerations that should be applied to calculating the compensation scale for them. Compensation scale calculations can in principle be applied in a similar manner using population modelling, however, quantitative information about how both adverse impacts and compensation measures modify demographic rates is often lacking.

10. Based on the reviewed evidence, we make the following recommendations:

    i) Compensation calculations should follow an approach that reflects population age structure and dispersal behaviours of Kittiwake (conceptually similar to the Hornsea 3 approach), while constraining assumed dispersal rates such that the artificial nest structure is self-sustaining under biologically reasonable demographic rates, noting that the evidence base for the latter is limited.

    ii) Compensation calculations should be made fully transparent and reproducible, and conducted in a way that is insensitive to software choice.

    iii) Monitoring of ANSs is central to our recommended approach with an initial priority to ascertain rates and extent of ANS colonisation and to ensure breeding productivity is sufficient to maintain the ANS population. Such monitoring data should greatly facilitate future modelling efforts aiming to evaluate their efficacy. This should ideally also include baseline monitoring both prior to and during operation and regular resighting efforts of ringed birds at the ANS and colonies within likely range of dispersing recruits from the ANS. Adaptive management strategies should be applied if the observed demographic rates are evidenced to significantly diverge from those assumed in the compensation calculations.

    iv) Given the scale of proposed ANSs, monitoring data must feed into the Seabird Monitoring Programme to facilitate meaningful inferences of the status of Kittiwake populations in the region.

    v) Current evidence to support the efficacy of ANSs as compensation for Kittiwake mortality at offshore wind farms is limited, but monitoring of future planned ANS is required to quantify their impact.

1. General introduction

1.1. Background

The increased development of offshore wind farms (OWFs) to expand provision of renewable energy is a key UK strategy for combating climate change (Kaldellis & Zafirakis 2011), with the UK government pledging to radically increase the amount of energy generated by offshore wind by 2030 (UK Government 2024). However, OWFs have the potential to cause adverse impacts to seabird populations, including through increased mortality via turbine collision (Furness et al. 2013), displacement/attraction (Dierschke et al, 2016) and barrier effects (Masden et al. 2009).

Any plan or proposal (e.g. proposed OWF) that has the potential to adversely affect any features (e.g. seabirds) of a designated Special Protection Area (SPA) site must be subject to a three-stage Habitat Regulation Assessment (HRA). In Stage 1, initial screening is conducted to assess whether the proposals are likely to result in significant effects. Where significant effects cannot be ruled out, the HRA proceeds to Stage 2, where appropriate assessment (AA) is used to perform an 'integrity test' to determine whether these significant effects will cause adverse effects on integrity (AEoI) of the designated site. For proposals that do not pass the integrity test, Stage 3 involves assessment of alternative solutions and consideration of imperative reasons of overriding public interest (IROPI). The use of compensatory measures to address AEoI may be employed as a last resort for proposals that can prove a lack of alternatives and IROPI. For further information see Natural England (2021).

In recent years, derogation cases have been required to enable the consent of several proposed OWFs in England due to concerns about negative impacts on the seabird features of SPAs. Compensation measures to offset seabird mortality arising as a consequence of OWFs being built have therefore been proposed, including the development of ANSs to facilitate establishment of new breeding colonies and provide additional breeding birds into the existing population. This includes the Black-legged Kittiwake (*Rissa tridactyla*, hereafter 'Kittiwake'), a nationally Red-listed and globally vulnerable species (BirdLife International 2019, Stanbury et al. 2024) which have experienced a population decline within the UK and Republic of Ireland (Burnell et al. 2023). The main concern created by OWFs for Kittiwakes appears to be around risk of collision (Black et al. 2019), although issues around displacement are starting to warrant further attention, at least in Scotland (NatureScot 2023). ANS have been approved as a priority compensation measure for Kittiwakes (DESNZ 2025). However, there is significant uncertainty regarding the efficacy of ANS compensation measures, particularly the suitability of methods used to calculate the required scale of compensation. There are three overarching steps to these calculations:

1. estimate annual mortality as a result of turbine collision at the proposed OWF using Collision Risk Modelling — the compensation target;
2. calculate the number of breeding pairs required at the ANS to produce sufficient recruits (i.e. breeding birds) to offset the predicted mortality — the compensation population;
3. apply compensation ratio (a multiplier applied to the calculated compensation population).

The compensation population is the estimated number of breeding pairs required to produce an annual number of new recruits equating to the compensation target.

With respect to Step 1, in the context of this report, the compensation target exclusively relates to Kittiwake mortality at the wind farm as a result of turbine collision. It does not account for Kittiwake mortality that may occur elsewhere as a result of the wind farm, such as through displacement or reduced survival rate. However, incorporation of Kittiwake mortality arising from these avenues can be incorporated into the compensation target. The knowledge gaps and uncertainties around mortality estimates derived from Collision Risk Models have been discussed in detail elsewhere (Cook et al. 2025, Croll et al. 2022). An assessment of the appropriateness of these calculated values, for any of the reviewed projects, was outside the scope of this review. However, it is important to note that the uncertainty of the resulting estimates of the compensation target directly influence the compensation population calculated by any of the reviewed methods.

In this report we focus on Step 2, i.e. calculation of the estimated number of required breeding pairs at the ANS to provide the agreed number of recruits, for which the methods are not consistent between recently consented or proposed OWF developments. In particular, there is stakeholder disagreement regarding whether all recruits produced at an ANS should count towards the compensation target (hereafter the 'new colony' approach), or whether only those that are surplus to recruits that would have otherwise been produced at the impacted SPA in the absence of the ANS should count (hereafter the 'surplus recruits' approach). The surplus recruits approach would represent a higher target for a given OWF since the compensation target is calculated by subtracting the counterfactual recruits from the total number of recruits. The new colony approach fundamentally relies on the assumption that birds breeding at the ANS would not have bred elsewhere, which in turn implies there being a substantial existing pool of adult non-breeders who are not recruiting into the metapopulation due to lack of appropriate nesting habitat.

With regards to Step 3, a review of the use of compensation ratios was outside of the scope of this review. However, it was noted that compensation ratios were used by some OWFs and not others, and where used, the values of the compensation ratios differed across OWFs.

1.2. Report objectives

The aim of this report is to provide independent expert advice to the Offshore ANS Implementation Group of the Collaboration on Offshore Wind Strategic Compensation (COWSC) programme on the efficacy and suitability of methods used to calculate the scale of compensation measures required for OWF impacts (Step 2), with a focus on the provision of ANS for Kittiwakes to compensate for collision mortality. This report has three main objectives:

1. to provide a full review of current methods for calculating the size of the compensation population required to offset impacts to Kittiwake populations based on the development of onshore and offshore ANS, and if necessary, propose and justify alternative methods;
2. make clearly justified recommendations on the calculation of scale for compensatory measures to inform best practice guidance for offshore wind farm HRA derogation cases, and if possible, provide a supplementary tool, that will allow the recommended method(s) to be implemented;
3. discuss the suitability of the recommended methods for other species and compensation scenarios.

2. Literature review

2.1. Methods used to calculate scale of compensation for Kittiwake mortality at OWFs

Recently consented or proposed OWF developments in English waters identified by Natural England were reviewed to evaluate the methods used to calculate the required scale of compensation for predicted Kittiwake mortality resulting from the proposals. These OWF developments included (in order of consent date):

- Hornsea 3 – consent granted in December 2020
- Norfolk Boreas – consent granted in December 2021, and
- Norfolk Vanguard – consent granted in February 2022 (hereafter collectively referred to as the Norfolk Projects, along with Norfolk Boreas)
- East Anglia ONE North (East Anglia 1N) – consent granted in March 2022, and
- East Anglia TWO – consent granted in March 2022 (hereafter collectively referred to as the East Anglia developments, along with East Anglia ONE)
- Hornsea 4 – consent granted in July 2023
- Sheringham Shoal Offshore Wind Farm Extension Project and Dudgeon Offshore Wind Farm Extension Project (SEP & DEP) – consent granted in April 2024
- Three Round 4 projects included in The Crown Estate's (TCE) Kittiwake Strategic Compensation Plan: Dogger Bank South West, Dogger Bank South East and Outer Dowsing Offshore Wind (hereafter

collectively referred to as 'Round 4' as the application comprised all three; TCE, 2025) — pending consent at the time of writing.

Taken together, these developments anticipate the need for a combined compensation population of c. 3,000 breeding pairs and associated proposals suggest the provision of 4,200–7,200 ANS spaces.

2.1.1. Calculation steps to determine scale of compensation

The methods used by the OWFs to calculate the size of the compensation population varied across the developments (Table 1 and Appendix 1). The method applied by Hornsea 3 was the most comprehensive in terms of the number of steps and biological features involved in the methodology, including classifying the population into multiple age classes. This method estimated breeding adult mortality and the required contribution of recruits for each age class, while also accounting for adult and natal philopatric dispersal rates. Although this is not a 'surplus bird' approach by definition (since the number of birds required was not assessed against a counterfactual of birds produced elsewhere), it is not strictly a 'new colony' approach — at least conceptually — because only the dispersing birds counted towards the compensation target. This approach is conceptually attractive as it explicitly separates birds recruiting back to the ANS from those recruiting back into the SPA network. However, it is the most parameter-rich approach, and the adequacy of parameter choices is hard to assess (see Section 2.1.2; Appendix 2). Although a larger number of recruits dispersing into the existing network is beneficial for achieving the compensation target, populations with high dispersal rates may be less likely to be self-sustaining. Hornsea 4 used a reduced version of this method which did not account for dispersal, thereby following a 'new colony' approach where all birds produced at the ANS counted towards the compensation target under the assumption that recruits produced at the ANS would not have been produced elsewhere in absence of the ANS. Round 4 presented both approaches used by Hornsea 3 and Hornsea 4, stating that the Hornsea 3 approach was preferred.

In contrast, the methods employed by the Norfolk and East Anglia developments did not include dispersal or classification of an age-structured population, but did consider parameters that were unaccounted for in the compensation population calculations for Hornsea 3 and 4. These developments employed a 'surplus' bird approach (where only the surplus birds above a defined baseline counted towards the compensation target), although the definition of the 'surplus' differed between the developments. For the Norfolk Projects, the 'surplus' recruits were those generated in excess of counterfactual recruits that would have otherwise been produced at the SPA in absence of the ANS. For the East Anglia applications, the surplus was calculated as those in excess of the number required to replace mortality at the ANS and ensure the ANS population is self-sustaining. Conceptually, whether the Norfolk or East Anglia developments would result in a higher compensation target depends on whether the difference between productivity at the SPA and ANS is greater or less than the estimated productivity rate to maintain a stable population; if SPA populations are declining, the East Anglia approach sets a higher bar for the compensation target as a greater number of recruits would be needed to replace the declining population. However, the Norfolk and East Anglia developments did not explicitly account for natal (or adult) dispersal. Consequently, all surplus recruits produced at the ANS counted towards the compensation target, when in reality only a proportion of those birds would disperse into existing colonies (including the impacted SPA) and the rest would remain at the ANS.

The approach proposed by SEP & DEP was unique in that it aimed to improve the nesting success of an existing ANS structure rather than create new artificial habitats. This involved the proposed removal of the south face of the existing Saltmeadows tower ANS at Gateshead (on which nest breeding productivity is 50% lower than that of the other faces) and installing two new north-facing faces. As such, this approach was neither a 'new colony' nor a 'surplus bird' approach as it did not depend on an existing pool of non-breeders seeking nest sites, but rather depended on relocation of the birds previously located in the suboptimal south face. We have termed this the 'relocation' approach in Tables 1 and 2.

Comparing the methods used across OWFs reveals that there are unique merits to each method. However, none fully addresses the need for the ANS to: 1) compensate for turbine collision mortality, 2) replace birds lost due to natural mortality at the ANS, and 3) account for the fact that only a portion of birds produced will disperse to the existing network. However, many of these unaccounted-for elements were qualitatively discussed in the OWF documentation, with some suggesting that the calculated compensation scale should be sufficient to also cover these additional losses because precautionary approaches were used (e.g. through use of upper 95% confidence interval mortality estimates or application of compensation ratios).

Table 1: Methods of calculating the required scale of compensation for predicted Kittiwake collision related mortality in recently consented or proposed OWFs. | = "according to"; A = age; AD = adult dispersal; ANS-SS = breeding productivity required for the ANS population to be self-sustainable; AS = adult survival; BP = breeding productivity; FNo= number of fledglings; JS = juvenile survival; ND = natal dispersal; NNo = number of nests; PNo = number of breeding pairs; RA = recruit age; RNo = number of recruits; SBP = surplus breeding productivity; SPA-BP = SPA breeding productivity.

<table>
<tr><th>Development</th><th>Approach</th><th>Key steps outlined in methods</th><th>Method elements</th></tr>
<tr><td>Hornsea 3</td><td>New colony (accounting for dispersal)</td><td>1. Calculate required number of recruits, accounting for natal dispersal (RNo | ND)
2. Calculate predicted age distribution of recruits (RA)
3. Calculate number of fledglings needed by calculating number of birds in each age category required to contribute number of new recruits, plus those that survived previous age category (FNo | AS)
4. Calculate number of breeding pairs required to achieve number of fledglings based on productivity rate (PNo | BP)
5. Calculate number of breeding pairs required, accounting for age distribution of population, adult survival and adult dispersal (PNo | A, AS, AD)</td><td>1. RNo | ND
2. RA
3. FNo | AS
4. PNo | BP
5. PNo | A, AS, AD</td></tr>
<tr><td>Norfolk Boreas & Norfolk Vanguard</td><td>Surplus recruits</td><td>1. Calculate required number of fledglings, accounting for juvenile survival (FNo | JS)
2. Calculate surplus breeding productivity based on productivity rates of ANS and Flamborough and Filey Coast (FFC) SPA (SBP | SPA-BP)
3. Calculate number of nests needed to provide required surplus number of recruits based on surplus productivity (NNo | SBP)</td><td>1. FNo | JS
2. SBP | SPA-BP
3. NNo | SBP</td></tr>
<tr><td>East Anglia 1N & East Anglia 2</td><td>Surplus recruits</td><td>1. Calculate required number of fledglings, accounting for juvenile survival (FNo | JS)
2. Calculate surplus breeding productivity based on breeding productivity of ANS and assumed breeding productivity required for the ANS to be self-sustainable (SBP | ANS-SS)
3. Calculate number of nests needed to provide required number of recruits based on surplus productivity (NNo | SBP)</td><td>1. FNo | JS
2. SBP | ANS-SS
3. NNo | SBP</td></tr>
<tr><td>Hornsea 4</td><td>New colony</td><td>1. Calculate predicted age distribution of juvenile recruits (RA)
2. Calculate number of fledglings needed to achieve number of juvenile recruits by calculating number of birds in each age category needed to contribute number of new recruits, plus those that survived previous age category (FNo | AS)
3. Calculate number of breeding pairs required to achieve number of fledglings based on productivity rate (PNo | BP)</td><td>1. RA
2. FNo | AS
3. PNo | BP</td></tr>
<tr><td>SEP & DEP</td><td>Relocation</td><td>1. Calculate required number of fledglings, accounting for juvenile survival (FNo | JS)
2. Calculate required number of fledglings, accounting for natal dispersal (FNo | ND)</td><td>1. FNo | JS
2. FNo | ND</td></tr>
<tr><td>Round 4</td><td>-</td><td>Presented methods from both Hornsea 3 and 4</td><td>-</td></tr>
</table>

Table 2 shows comparisons of the compensation target (i.e. predicted annual mortality) and the calculated compensation population across OWFs. Some developments applied a compensation ratio, while others did not. To facilitate comparison, we recalculated compensation populations without this ratio. We then derived the 'compensation magnitude', i.e. the ratio of the compensation target and compensation population. As shown, the East Anglia developments had the highest compensation magnitude, whereas the Norfolk Projects – which also used a surplus bird approach – had one of the lowest.

Table 2: Comparisons of compensation magnitude, i.e. the ratio between compensation target and the calculated compensation population, once compensation ratios have been removed from calculations for comparability of the approaches used.

OWF	Approach	Compensation target[1]	Compensation population[1]	Compensation population in absence of compensation ratio	Compensation magnitude
Hornsea 3	New colony (accounting for dispersal)	73	467	467	1 : 6.40
Norfolk Boreas	Surplus birds	14	145	47	1 : 3.36
Norfolk Vanguard	Surplus birds	21	215	71	1 : 3.38
East Anglia 1N	Surplus birds	2	60	20	1 : 10.0
East Anglia 2	Surplus birds	2	60	20	1 : 10.0
Hornsea 4	New colony	43	230	115	1 : 2.67
SEP & DEP	Relocation	17	68	68	1 : 4.00
Round 4	New colony (accounting for dispersal)	338	1872	1872	1 : 5.54
[1] Rounded to the closest whole number					

2.1.2. Demographic parameters

Table 3 summarises the values of demographic parameters used in the compensation calculations for the OWF developments. The only values of parameters consistent across the developments were for adult and juvenile survival, taken from Horswill & Robinson's (2015) literature review of seabird demographic rates across the UK.

Estimated breeding productivity at the ANS varied across the developments. The East Anglia and Norfolk developments used empirical estimates from three colonies in north-eastern England where Kittiwakes nest on artificial structures ranging from bespoke towers to bridges and buildings (Lowestoft, River Tyne and Dunbar respectively) in the 2021 breeding season, commissioned by the Norfolk Projects. Norfolk used the highest of these estimates, while East Anglia used a value slightly below the average. Hornsea 4 adopted the average productivity for the east of England based on Horswill & Robinson's (2015) review of demographic parameters for seabirds breeding in the UK. Hornsea 3 also used estimated breeding productivity from Horswill & Robinson (2015), but scaled the east of England figure by the estimated productivity for first and subsequent breeding attempts.

Two approaches to recruitment age (i.e. the age that birds reach sexual maturity) were used across the developments. Horswill & Robinson's (2015) average estimate of four years old was used by the Norfolk, East Anglia and SEP & DEP developments, whereas Hornsea 3 and Hornsea 4 used proportional estimates of recruitment age from 0–10 years based on Coulson (2011). Using an age structured approach may allow for improved biological realism, although a more parsimonious age structure is likely easier to validate against existing and future monitoring data.

Table 3: Demographic parameters used to calculate the size of the compensation population estimated to produce the compensation target for predicted Kittiwake mortality due to collision in consented or proposed OWFs. Round 4 is not shown as they presented results using both the Hornsea 3 and 4 methods (stating that Hornsea 3 was the preferred method).

Parameter	Hornsea 3	Norfolk Projects	East Anglia 1N & 2	Hornsea 4	SEP & DEP
Survival rate – juveniles	0.790 (Horswill & Robinson 2015)	0.790 (Horswill & Robinson 2015)	0.790 (Horswill & Robinson 2015)	0.790 (Horswill & Robinson 2015)	0.790 (Horswill & Robinson 2015)
Survival rate – adults	0.854 (Horswill & Robinson 2015)	0.854 (Horswill & Robinson 2015)	0.854 (Horswill & Robinson 2015)	0.854 (Horswill & Robinson 2015)	0.854 (Horswill & Robinson 2015)
Breeding productivity – ANS	0.819[1] (Derived from Horswill & Robinson 2015)	1.2 (Carter 2014, MacArthur Green 2021b)	1 (MacArthur Green 2021b)	0.819[1] (Derived from Horswill & Robinson 2015)	–
Breeding productivity – SPA	–	0.6 (Aitken et al. 2017)	–	–	–
Breeding productivity to sustain ANS population	–	–	0.8 (Coulson 2017)	–	–
Recruitment age	Proportional estimates from 2–10 yrs (Coulson 2011)	4 years (Horswill & Robinson 2015)	4 years (Horswill & Robinson 2015)	Proportional estimates from 2–10 yrs (Coulson 2011)	4 years (Horswill & Robinson 2015)
Natal dispersal	Two scenarios: 0.77 & 0.89 dispersal of new recruits (Coulson 2011)	–	–	–	50% new breeding adults disperse to SPA (Stroud et al. 2016)
Adult dispersal	0.012 (Horswill & Robinson 2015)	–	–	–	–

[1] Derived using an average breeding productivity of 0.561 for 1st attempt breeders and for ≥2nd attempt breeders of 0.862. Based on an average survival rate of 0.854, they assumed 14.6% of birds would be 1st attempt breeders and 85.6% of birds would be ≥2nd attempt breeders, averaging at an overall breeding productivity of 0.819.

Only SEP & DEP and Hornsea 3 incorporated estimated rates of natal dispersal into existing colonies. SEP & DEP employed the more conservative of these estimates, using a proportion of 0.5 dispersal obtained from the Stroud et al. (2016) review of SPA UK status in the 2000s. Hornsea 3 used two different scenarios of sensitivity of 0.77 and 0.89 based on Coulson (2011) and presented results according to each value. However, the use of these natal dispersal figures as estimates of net dispersal into the metapopulation is inadequate. The figures given in Coulson (2011) are actually a measure of philopatry, as opposed to net dispersal rates of birds. Hence, they represent gross dispersal (i.e. the proportion of each cohort born at the colony which then went onto recruit elsewhere) without accounting for the fact that the same colony received recruits born at other colonies every year (Coulson & Coulson 2008). For the ANS to provide an ongoing net benefit to the network, the colony needs to export more birds than it receives as recruits, while also maintaining a stable or growing local population. This can only be achieved with net dispersal rates that are smaller than the gross natal dispersal rate (Appendix 2).

Finally, adult dispersal was only accounted for by Hornsea 3, at a low annual rate of 0.012 sourced from Horswill & Robinson (2015), which also likely represents a gross dispersal estimate.

2.2. Expected timescales for achieving compensation target

Initial colonisation of the ANSs needs to occur through dispersal of Kittiwakes (first-time breeders or older adults) from existing colonies. However, little data are available at a sufficient scale to identify the underlying metapopulation dynamics of Kittiwakes, and colony formation is poorly understood as a result (O'Hanlon et al. 2021, 2023). Across all the developments, the ANSs were initially planned to be operational for four breeding seasons prior to operation of the OWF, to ensure production of the first recruits before OWF operation (based on an assumed average recruitment age of four years old). However, permission was granted for Hornsea 3 to reduce the period of time between ANS and OWF operation from four to two breeding seasons, and Hornsea 4 have applied for the same.

Timescales for reaching the compensation targets were estimated by the Norfolk Projects and Hornsea 4. Both developments modelled multiple scenarios of annual colony growth, initial colony size and breeding productivity. The Norfolk Projects modelled the following four scenarios:

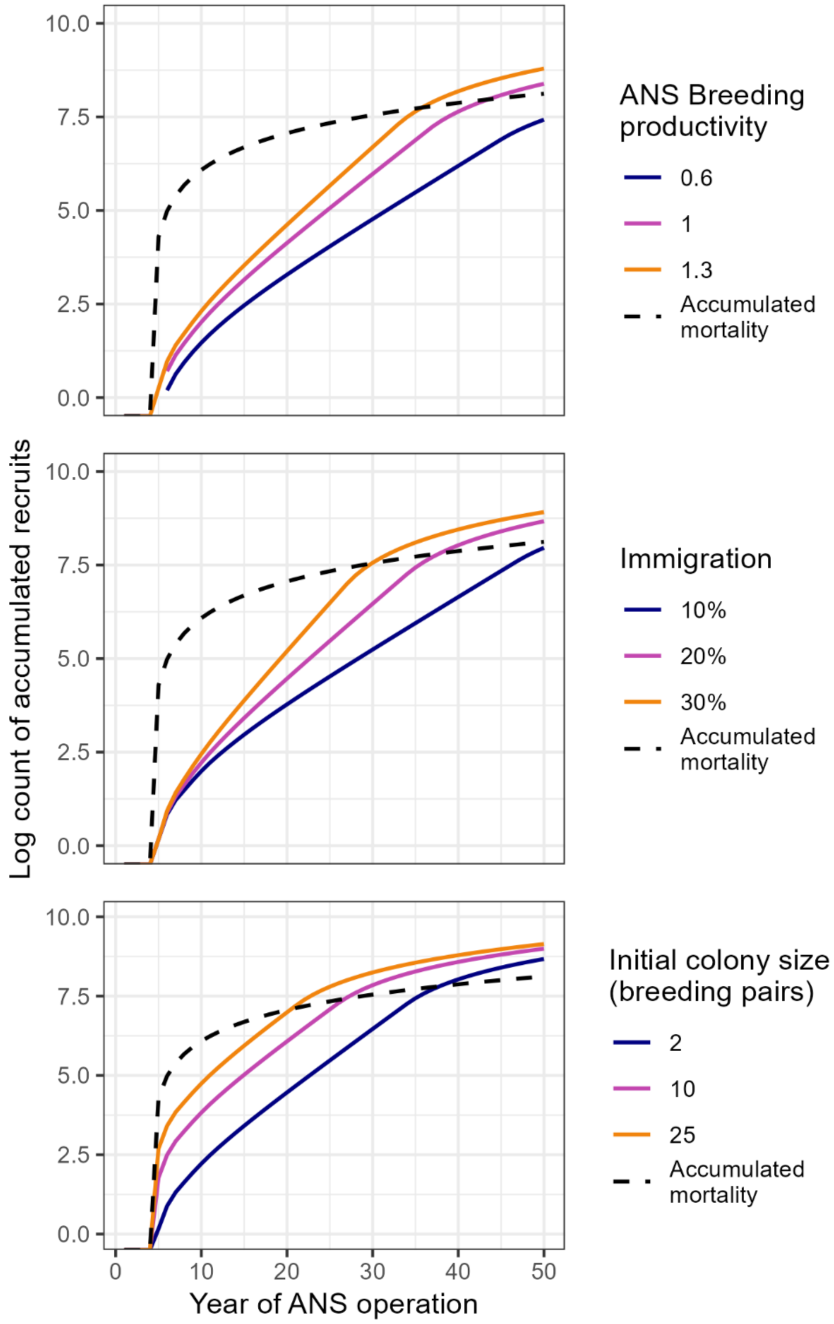
1. Annual colony growth 20%, initial colony size 25 pairs, surplus breeding productivity 0.6;
2. Annual colony growth 20%, initial colony size 25 pairs, surplus breeding productivity 0.8;
3. Annual colony growth 20%, initial colony size 50 pairs, surplus breeding productivity 0.6;
4. Annual colony growth 20%, initial colony size 75 pairs, surplus breeding productivity 0.6.

In the worst-case of the Norfolk Project scenarios (Scenario 1), accumulated production of adults was estimated to surpass accumulated mortality debt 11 to 12 years after initial operation of the OWF, presuming the ANS was operational for four breeding seasons prior. In the best case of these scenarios (Scenario 4), payback was estimated to occur in the first year of ANS operation.

Numerous scenarios were modelled for Hornsea 4. Two scenarios of initial colony size were considered: one and 20 breeding pairs, based on empirical data from Coquet Island and 14 populations in Alaska (Kildaw et al. 2005) respectively. For each of these scenarios, three trajectories of population growth rate were explored:

1. Observed colony growth rates from Coquet Island, Northumberland (representing population growth in locations where Kittiwakes have not previously bred);
2. Observed colony growth rates from Marsden Cliff, Tyneside;
3. Logistic growth rate model using three separate growth rates:
    a) 20%, based on advice provided by Natural England to the Norfolk Boreas application
    b) 50% (Coulson 2011)
    c) 80% (Coulson 2011).

Figure 1: Estimated timescales for payback of Kittiwake mortality due to turbine collision at offshore windfarms based on varying assumed values of breeding productivity at the ANS, immigration rate and initial colony size. Figures represent an assumed example compensation target of 73 birds per year, an ANS capacity of 467 nests, and a new colony approach to payback (i.e. all recruits count towards the compensation target). 'Payback' is achieved when the accumulated number of recruits exceeds the accumulated mortality (i.e. where the black dashed line crosses the coloured lines). All scenarios assumed adult and juvenile survival rates of 0.854 and 0.790 respectively. Unless stated otherwise (i.e. if a different value was being tested), 'standard' values of breeding productivity, immigration and initial colony size were 1.2, 0.2 and 2 respectively.



Four scenarios of breeding productivity were also explored:

1. Observed breeding productivity for each year of colony growth at Coquet Island;
2. 0.8 fledglings per nest ('low' productivity), based on the threshold required for a self-sustaining population calculated by Coulson (2017);
3. 1.025 fledglings per nest ('medium' productivity), based on the 2013–2017 average for Lowestoft;
4. 1.38 fledglings per nest ('high' productivity), based on the peak productivity for 2021–2023 at Sizewell Rigs.

Juvenile and adult survival rates from Horswill & Robinson (2015) were used in all scenarios. Across the Hornsea 4 simulations, accumulated production of adults was estimated to surpass accumulated mortality debt between 16–39 and 9–22 breeding seasons after operation of the ANS for initial colony sizes of one and 20 breeding pairs respectively.

In addition to the modelling conducted by the Norfolk Projects and Hornsea 4, we ran simulations to demonstrate that the estimated timescales for payback of mortality may be highly sensitive to the assumed value of demographic parameters used in the calculations. Figure 1 demonstrates the impact of differing assumed values of immigration rate, initial colony size and breeding productivity by simulating timescales for payback of an example compensation target of 73, using an ANS capacity of 467 nests (which is assumed to be able to reach a 100% occupancy rate). As shown, the simulated timescales for payback range by decades between the scenarios. For the lowest assumed values of breeding productivity at the ANS (0.6) and immigration rate (10%), the simulated ANS does not achieve payback within its assumed lifespan of 50 years. This variation in estimated timescales highlights the influence of demographic parameters with highly uncertain values, impacting whether payback can realistically be achieved within the lifespan of the ANS.

2.3. Proposed Kittiwake monitoring at OWFs

Common across the OWF developments was a promising suite of planned monitoring at the ANS and nearby colonies (Table 4), with the purpose of tracking the performance of the ANS as a compensation measure. For all OWFs except SEP & DEP, monitoring was divided into 'core' and 'additional' proposals, with core monitoring representing the minimum requirements. For the East Anglia and Norfolk Projects, core monitoring was proposed for the duration of ANS commission whereas additional monitoring was planned only for the first three years (with potential for extension), despite the worst-case scenario for payback for the Norfolk Projects being estimated at 11 to 12 years. Where colour ringing was proposed, adults and chicks were planned to be ringed for the first five and 10 years respectively. For Hornsea 3, Hornsea 4 and Round 4, monitoring was proposed for the duration of the OWF operational phase.

SEP & DEP acknowledged that nearby OWF developments would be undertaking similar monitoring and proposed integration of monitoring needs between other developers to provide a coherent monitoring programme. At the time of writing, Round 4 had not yet recommended additional monitoring as this was to be explored post-consent. SEP & DEP, the East Anglia developments and the Norfolk Projects stated that monitoring results would be shared with the Kittiwake Compensation Steering Group (KCSG) led by TCE. However none stated that the results would be shared with the BTO/JNCC/RSPB Seabird Monitoring Programme (SMP), which has its own handbook of methods for assessing breeding abundance and productivity (Walsh et al. 1995) and collates data annually across the UK and Ireland. Data from the SMP, along with the four periodic seabird censuses, form the basis for the assessment of the conservation status of this species (Stanbury et al. 2024). Birds breeding on artificial offshore structures such as oil rigs are already underrepresented in SMP (BTO, unpublished data). At the scale of proposed ANS provisioning, the lack of feedback of information on ANS population sizes and productivity into the national monitoring scheme therefore risks a situation where conservation status assessments are made on an incomplete subset of the breeding population. SMP staff facilitate the addition of new recording sites (including on artificial offshore structures), so there should be no foreseeable barriers to ANS locations being included in SMP (S. Harris, pers. comm.)

Table 4: Proposed OWF monitoring. AON = Apparently occupied nests. Monitoring marked with an asterisk indicates 'core' (i.e. minimum) monitoring, with remaining monitoring classed as 'additional' monitoring (inexhaustive).

Monitoring	Hornsea 3[1]	Norfolk Projects	East Anglia 1N & 2	Hornsea 4[1]	SEP & DEP[2]	Round 4[3]
At proposed ANS						
Full colony breeding population size (AONs)	✓*	✓*	✓*	✓*	✓*	✓*
Trace nest counts (prospecting first-time breeders)	✓*			✓*		✓*
Productivity	✓*	✓*	✓*	✓*	✓*	✓*
Colour ringing – chicks	✓	✓*	✓*	✓		✓*
Colour ringing – adults	✓[4]	✓*	✓*	✓[4]		
Systematic ring resighting	✓[4]			✓[4]		
Monitoring of colonisation rates during colony establishment	✓*			✓*		✓*
Relationship between nest position and breeding success		✓	✓			
Diet studies	✓	✓	✓	✓		
GPS tagging of adults to assess breeding season foraging behaviour	✓*	✓	✓			
At other colonies[5]						
Colony counts and productivity surveys prior to ANS operation	✓*	✓[6]		✓* [7]		
Breeding population size (AONs)		✓	✓		✓*	✓*
Trace nest counts (prospecting first-time breeders)						✓*
Productivity		✓	✓		✓*	✓*
Colour ringing – chicks		✓	✓			
Ring resighting campaigns		✓	✓			

[1] Proposed at onshore ANS, but not nearshore ANS due to accessibility. [2] For SEP & DEP, additional monitoring was not proposed as the Tyne Kittiwake colonies are already monitored by local groups. [3] Additional monitoring for Round 4 to be proposed post-consent, which had not yet been granted at the time of writing. [4] Colour ringing and systematic ring resighting of adults were jointly proposed as a Retrapping Adults for Survival programme. [5] Defined as follows for OWFs: SEP & DEP: Other sites in Lowestoft and/or Gateshead | East Anglia 1N & 2 and Norfolk Projects: Within 100 km of the compensation population, where feasible | Hornsea 3 and 4: Six colonies within 20 km of the ANS | Round 4: Not yet defined. [6] Breeding success surveys for the 2021 breeding season were commissioned prior to the proposals. [7] Conducted by Hornsea 3, but transferable to Hornsea 4.

2.4. Additional factors potentially influencing Kittiwake population dynamics

Kittiwake population dynamics are likely to be influenced by many additional factors not accounted for in the compensation scale calculations, leading to potential uncertainty in the efficacy of ANS as a compensation measure. These factors are discussed in the following sections. Many of these factors (including the role of non-breeders, source–sink dynamics and density dependence) are considered in the ongoing Offshore Renewables Joint Industry Programme (ORJIP) MetaKitti project, which aims to model Kittiwake metapopulation dynamics and their implications for OWF compensatory measures. Preliminary outputs of the MetaKitti project describe a stage-structured model similar to that of Horswill et al. (2022), – which distinguishes age (adult/sub-adult) and breeding status (breeder/floater), and accounts for three types of density dependence – that can reconstruct observed colony population dynamics. For each modelled colony, the MetaKitti model is able to estimate colony size, carrying capacity, breeding success and survival over time, alongside the proportion of recruitment contributed to the wider metapopulation, albeit with large uncertainty intervals owing to the sparsity of colony-specific data. Initial results show an overall picture of decline for the modelled colonies. The project's next steps involve analysing colony source-sink dynamics and generating future predictions (Matthiopoulos 2025).

2.4.1. Spatial and temporal variation of demographic parameters

Demographic parameters for seabirds, such as survival and breeding productivity rates, are subject to high levels of spatial variability across populations (Davis et al. 2005, Frederiksen et al. 2005, 2021, Sandvik et al. 2012). However, the majority of parameter values used in the compensation calculations were average values for the UK obtained from literature reviews (Table 3). Hence, values may not be representative of realised demographic rates at the proposed ANS or impacted SPA, introducing uncertainty into the compensation calculations. For breeding productivity, which benefits from more long-term empirical datasets than other demographic rates (Horswill et al. 2021), local data were utilised by the Norfolk and East Anglia projects whereas regional estimates were used by Hornsea 3 and 4. However, Searle et al. (2020) showed that population viability models that used breeding productivity data from the specific colony being modelled had improved performance than those that used breeding productivity values aggregated over space. For other demographic rates, use of mean values likely reflects the lack of easily accessible local estimates, especially survival, for which little data exist (O'Hanlon et al. 2021). However, elasticity analysis has shown that adult survival has a higher influence on population growth rate than reproduction in Kittiwake populations (Horswill et al. 2021).

In this context, it is also important to note that any thresholds based on a single demographic rate – such as the productivity threshold for a self-sustaining colony of 0.8 estimated by Coulson (2017) – are only valid in the context of other demographic rates operating at the time. Single-rate thresholds are therefore to be treated with caution and are unlikely to be universally valid. Survival rates are also likely to be impacted by fine-scale factors, such as availability of prey stock (Frederiksen et al. 2004, 2005, Reiertsen et al. 2014); so, inability to include location-specific survival estimates introduces large uncertainty into the compensation calculations. Further, demographic datasets that do exist are mostly based on natural colonies rather than ANSs. Although many colonies have established naturally on artificial structures, information about the population size and demographic rates at these sites is lacking (but see Christensen-Dalsgaard et al. 2019). This limits our ability to accurately derive parameter estimates for these sites.

Although the compensation calculations assume constant values of demographic parameters over time, demographic rates are also subject to both long- and short-term temporal variation. For example, Kittiwake populations have been in decline across the UK since the Seabird Colony Register (SCR Census; 1985–1988) (Lloyd et al. 1991). The suitability of survival and productivity rates utilised in the compensation calculations may therefore depend on the context and trajectory of the populations from which they were taken at the time of recording, and how these compare to the trajectory of the ANS populations. Horswill et al. (2022a) found that incorporating observed long-term temporal trends of productivity data alongside annual stochasticity in a population viability analysis had a large influence on model projections, resulting in a predicted population size 47% lower than the model only accounting for stochasticity. This demonstrates that ignoring the potential for temporal trends in demographic parameters may lead to inaccurate compensation calculations. Although Kittiwake populations in England have remained relatively stable since the Seabird 2000 census (1998–2002) (Burnell et al. 2023), short-term environmental stochasticity can increase the demographic impact of parameters, even those with low elasticity (Horswill et al. 2021). Although long-term datasets are not yet available for ANS colonies, these studies highlight the importance of sustained data collection efforts at newly constructed ANS colonies to enable an assessment of ANS efficacy and aid future modelling efforts.

Lastly, demographic parameters are unlikely to be fully independent of each other, but correlations between demographic parameters are poorly understood (but see Appendix 2). For example, an experimental study evaluating the impact of supplemental feeding on Kittiwake breeding success and recruitment in the North Pacific (Vincenzi et al. 2015) found that surplus productivity at the breeding stage may be at least partially compensated for by decreased juvenile survival between fledging and recruitment. The study showed that although annual breeding success was up to twice as high for supplemented nests, gains in recruitment for those nests were on average only 20% higher than those for unsupplemented nests. Recruitment dynamics of the North Sea population are poorly understood and as such there is little knowledge whether similar compensatory effects are operating there. It is therefore unsurprising that none of the reviewed calculation approaches account for such compensatory effects. If surplus productivity at ANSs in the North Sea is indeed based on easier access to prey (as suggested e.g. by Christensen-Dalsgaard et al. (2019)) and similar compensatory effects operate, then efficacy assessments based on breeding productivity alone may be overly optimistic.

2.4.2. Colonisation and population growth rates

There is also large uncertainty around the colonisation dynamics of the ANS, particularly regarding the types of birds that may colonise and the rate of population growth. This, in turn, contributes to uncertainty in the predicted timescales for achieving the compensation targets.

Rapid colonisation of ANSs have been observed in the immediate vicinity of existing colonies and/or following the destruction of existing nesting space nearby (e.g. at the replacement ledges installed ahead of the demolition of the Lowestoft Pier Pavillion, at which 259 pairs were nesting five years following demolition; MacArthur Green 2021a). While robust data from naturally forming colonies are sparse, the available evidence suggests that colony establishment can be preceded by many years of intermittent breeding (e.g. Acker et al. 2017, Petersen, 2009) and that immigration is the dominant contribution to colony growth for at least 10 to 15 years (e.g. Coulson & Coulson 2008). However, the ANS scaling approaches discussed above all assume a much earlier contribution of locally produced recruits to the ANS population, i.e. that philopatric recruitment will begin in the fourth year of ANS operation based on an average breeding age of four years old. For this reason, ANSs are generally proposed to be functional for four years prior to operation across all the OWFs (although some have sought and been granted permission to reduce this period to two years prior). However, the majority of fledglings from a colony are thought to disperse elsewhere, particularly females (Coulson 2011). For example, at the North Shields colony the first philopatric male and female recruit only started breeding in the ninth and sixteenth breeding seasons respectively (Coulson & Coulson 2008).

Prior to any successful recruitment of birds fledged at the ANS, the ANS would be colonised from birds dispersing from other locations within the existing metapopulation. Typically, these immigrating birds are assumed to be prospecting first-time breeders from other colonies. However, dispersing Kittiwakes may also include established breeding individuals experiencing low or failing reproductive success (Boulinier et al. 2008, Ponchon et al. 2015, Acker et al. 2017). This decision to emigrate may also be influenced by local levels of breeding success in both the original and prospective colonies, which could be even more influential than individual breeding failure (Boulinier et al. 2008, Ponchon et al. 2015), potentially complicating estimations of emigration rates of established breeding birds.

In addition, there is large uncertainty regarding the prevalence and role of non-breeding adult birds (floaters) in Kittiwake populations, particularly since monitoring efforts tend to focus on the breeding population (Penteriani et al. 2011). However, omission of non-breeding adults from population models could potentially overestimate demographic variance and, if sabbatical birds re-enter the breeding population, underestimate population growth rate (Penteriani et al. 2011, Lee et al. 2017). Floaters may also serve as a buffer for the breeding population: for example, in instances of large-scale mortality, lost breeding birds could be replaced with non-breeders if the pool of floaters is of sufficient size (Penteriani et al. 2011). In a study based in Brittany, France, approximately 10% of the adult population were estimated to be non-breeders (Cam et al.

1998). Adult non-breeders may also have different demographic rates compared to breeders through differing patterns of habitat use (Lee et al. 2017), such as lower survival rates (Cam et al. 1998), so using global demographic parameters for both breeders and non-breeders (most likely to be estimated from the breeding population) may not be representative.

2.4.3. Metapopulation dynamics
Because individual Kittiwake colonies are not a closed system, migration between populations could influence the overall compensatory impact of the ANS. The efficacy of the ANS should therefore be determined in the context of metapopulation dynamics (Ruffino et al. 2020), i.e. connectivity between geographically separated populations (Levins 1969). Across the OWF developments, emigration from the ANS was only considered in the Hornsea 3 and Round 4 compensation calculations, while none accounted for immigration to the ANS. Currently, dispersal data may be difficult to incorporate as general understanding of Kittiwake metapopulation dynamics is poor (O'Hanlon et al. 2023). An unknown proportion of the Kittiwake population in UK waters breeds on offshore oil and gas platforms and associated infrastructure, and demographic rates in these locations are also generally unknown. Decommissioning of these structures introduces further uncertainty as it will likely result in the redistribution of existing breeders. However, Kittiwake metapopulation dynamics are a subject of active research and so could be incorporated into compensation calculations in the future. For example, Research Opportunity 3.1 of the Offshore Wind Strategic Monitoring and Research Forum (OWSMRF) seeks to quantitatively evaluate connectivity between Kittiwake colonies in UK regions relevant for offshore wind in order to inform the vulnerability of Kittiwake breeding at SPAs to OWF mortality (JNCC, 2022), including the ongoing ORJIP MetaKitti project.

Source–sink dynamics, i.e. the relative balance between births, deaths, immigration and emigration in metapopulation patches (Pulliam 1988), could also influence ANS efficacy. For example, Horswill et al. (2022b) identified that a Kittiwake colony at Skomer Island, Wales, was a sink population reliant on immigration. Reconstruction of observed population dynamics could not be achieved using philopatric recruitment alone, indicating that immigration played a key role. For an ANS to have a net positive impact on the existing metapopulation, it must be self-sustaining and facilitate higher breeding productivity than the impacted SPA. Otherwise, the ANS risks being a population sink and acting as an ecological trap (or 'attractive sink'), where birds have lower breeding productivity than they could elsewhere (Hale & Swearer 2016, Zhang et al. 2023). Ideally, a surplus bird approach should take both these factors into account. However, only the East Anglian developments accounted for the need for the ANS to be self-sustaining, and only the Norfolk Projects accounted for differences in breeding productivity between the ANS and SPA.

To facilitate evaluation of the impact of the ANS on the whole metapopulation, it is critical that monitoring at the ANS must be fed back into national monitoring programmes such as the SMP. However, it may be difficult to determine whether an ANS is acting as an ecological trap if baseline monitoring was not conducted prior to installation. This indicates a requirement for monitoring at the impacted SPA (and potentially other colonies) prior to operation of the ANS. However, a further aim of OWSMRF and the ORJIP MetaKitti project is to determine the source–sink dynamics of individual Kittiwake colonies (JNCC 2022), which could also facilitate comparison of source–sink dynamics before and after ANS operation for individual colonies modelled in a framework such as that proposed by the MetaKitti project.

2.4.4. Density dependence
Finally, the current methods of calculating ANS compensation scale do not consider processes of density dependence. Compensatory density dependence, i.e. where population growth is limited by carrying capacity and changes to demographic rates may offset each other, is evidenced in Kittiwakes by empirical observations and models of population dynamics (Horswill et al. 2017, Ruffino et al. 2020). For example, population growth is known to decline with increasing colony size (Coulson 2011, Ruffino et al. 2020) as a result of competition for resources within the carrying capacity of the population, which in turn can substantially influence demographic rates of individual colonies. Kitaysky et al. (2000) illustrated this by comparing breeding success of a small and large colony in a year of low food availability. In the smaller colony, Kittiwakes were able to increase their foraging distance and had reduced breeding productivity, whereas the larger colony experienced total breeding failure due to greater prey depletion. Not accounting for compensatory density dependence when modelling impacts of OWF collision is sometimes considered

a precautionary approach due to omission of processes that may offset mortality (Horswill et al. 2017). However, there is also evidence to support depensatory density dependence (accelerated population decline) in Kittiwake, attributed to increased predation at lower population densities (Horswill et al. 2017). Exclusion of density dependence from compensation calculations does therefore not necessarily represent a precautionary approach.

The total number of proposed ANS nest spaces across the reviewed OWFs comprises 5.76–9.87% of the total Kittiwake population in England, or 9.22–15.8% of the FFC SPA population, which is approximately equivalent to the number of breeding pairs lost between the most recent seabird censuses (Burnell et al. 2023). Full occupancy is, however, unlikely to be reached, firstly due to the scale of these sites, and secondly because occupancy of ANSs are often observed to be relatively low. For example, the Gateshead Kittiwake Tower at South Shields, Tyneside, has plateaued at an occupancy rate of 40% (Niras 2024). There is also likely to be variation in the attractiveness of new colonies (including ANS) to prospecting Kittiwakes, and the dispersal rates cited here largely reflect natural colonies which already support conspecifics or other seabird species. Colony size is likely to be limited by carrying capacity (i.e. the maximum population size that can be sustained by a particular environment according to available resources) rather than nest availability. This could inhibit the ability of the ANSs to reach their compensation target. Further, diminishing returns with additional ANS construction are likely, as there will be an upper limit to the number of satisfactory areas for ANS location and the number of birds able to emigrate to the ANS.

3. Possible modelling

As discussed in the previous sections, modelling efforts are currently limited by lack of data regarding the function of ANSs and their interactions with the existing Kittiwake population. The scope of possible future modelling efforts will be informed by available monitoring data at ANSs. All OWFs proposed monitoring of breeding productivity and colour ringing of chicks and adults to inform survival rates (except SEP & DEP which did not propose their own ringing since there is an existing local ringing group at the site). If successful, this productivity and survival data would facilitate modelling of the ANS as a steady-state closed system (i.e. not accounting for the wider metapopulation), including evaluating whether the compensation target has been achieved.

To assess the overall impact of the ANS on the existing Kittiwake metapopulation, data regarding migration between the ANS and existing colonies would be required. Ring resighting at neighbouring colonies within 100 km of the ANS was proposed by the East Anglia and Norfolk developments, which should provide data regarding natal and adult dispersal. However, ring resighting at neighbouring colonies was not proposed by Hornsea 3, Hornsea 4 or Round 4 (although Round 4 had not proposed additional monitoring as it was still pending consent at the time of writing), which comprise the largest proportion of nest sites (Table 2). Without these data, it would be difficult to determine the impact of the ANS on the existing metapopulation.

In addition, monitoring of existing nearby colonies prior to ANS construction (e.g. colony counts and breeding productivity surveys) would help to identify changes in source–sink dynamics of the metapopulation following ANS operation and determine whether the ANS is acting as an ecological trap (Rotem et al. 2013). Monitoring data for existing colonies may be available from the SMP, but additional effort may be required to ensure regular spatial/temporal coverage. Colony counts and/or breeding productivity surveys at neighbouring colonies were proposed by Hornsea 3 and the Norfolk Projects during ANS operation, but only the Norfolk Projects reported that they conducted surveys prior to ANS operation (the results of which were also utilised by East Anglia).

In terms of potential modelling frameworks, a matrix population model would be achievable using data only available at the ANS. This is, in part, facilitated by Coulson's (2011) proportional estimates of recruitment age utilised by Hornsea 3 and 4. If sufficient data are available for neighbouring colonies, frameworks representing movement between metapopulation patches could be explored, such as individual based models, integral projection models or a vec-permutation matrix model. This may permit modelling of an open population and/or better capture non-steady state dynamics. Using a Bayesian framework (as per the

MetaKitti project), known correlations between demographic parameters could be used to infer demographic rates for which data might be sparse (such as survival rates if ring resighting is low) (Horswill et al. 2021).

4. Compensation for species other than Kittiwake and by means other than ANS

The impacts of offshore wind farms are predicted to not only affect Kittiwake, but also other seabird features of SPAs and Special Areas of Conservation (SACs). When this occurs, it is necessary to compensate for all impacted features to maintain the integrity of the SPA and SAC network. In addition to ANS for Kittiwake, the Offshore Wind Environmental Improvement Package Library of Strategic Compensation Measures currently includes the designation of new marine protected areas or the extension of existing ones (for impacts to benthic SACs), as well as predator control at bird colonies. McGregor et al. (2022) provide a comprehensive review of potential compensation measures for nine qualifying features of eight English SPAs predicted to be impacted by OWF developments. These included:

- Lesser Black-backed Gull at Alde-Ore Estuary (AOE) SPA (collision mortality of breeding birds);
- Sandwich Tern at North Norfolk Coast (NNC) SPA (collision mortality of breeding birds);
- Guillemot at FFC SPA (displacement mortality of breeding birds);
- Red-throated Diver at Outer Thames Estuary (OTE) SPA (displacement habitat loss for wintering birds).

For breeding Lesser Black-backed Gulls at the AOE SPA, McGregor et al. (2022) assessed the efficacy of anti-predator fencing aimed at excluding Foxes.

For breeding Sandwich Terns at NNC SPA, McGregor et al. (2022) assessed four potentially successful compensation measures: (i) anti-predator fencing, aimed at excluding Foxes, (ii) control/eradication of Stoat; (iii) flood and vegetation control at colonies, (iv) closure of sandeel and sprat fisheries.

For breeding Guillemot at FFC SPA, McGregor et al. (2022) assessed the efficacy of two potentially successful compensation measures: (i) the closure of sandeel or sprat fisheries and (ii) the eradication of rats and other invasive mammals at sites outside of the FFC SPA.

For wintering Red-throated Divers at OTE SPA, McGregor et al. (2022) assessed: (i) the implementation of strict marine reserves and (ii) the removal of existing OWFs to maintain or improve the density and distribution of the species in the affected SPA. In principle, interventions at breeding sites similar to those proposed for SPA breeding are possible for Red-throated Divers, including the provision of artificial nesting structures (Nummi et al. 2013), but their effect on the qualifying feature of the SPA would likely be much less direct.

Fundamentally the scaling of proposed compensation measures can follow the same approaches as reviewed for Kittiwake ANS provision, that is using projections from structured population models to assess whether and when gains from successful compensation measures balance the predicted mortality caused by adverse OWF impacts. This approach was used in the efficacy assessments in McGregor et al. (2022) by means of stochastic population viability analysis.

However, any calculation method for compensation scaling based on population models relies on assumptions about how the proposed intervention modifies demographic parameters, which then lead to changes in the population dynamics that balance the adverse OWF impacts. The quality of the empirical evidence or estimates to inform these assumptions is therefore key, although in practice quantitative evidence may not be available. For example, in the case of Sandwich Terns at NNC SPA and Lesser Black-backed Gulls at AOE SPA, McGregor et al. (2022) had high confidence that compensation measures aiming at predator exclusion would be effective in principle given extensive evidence of positive effects (e.g. Robertson et al. 2015, Dalrymple 2023), but empirical evidence was lacking to inform the exact magnitude of the effects of predator exclusion. For some of the evaluated compensation actions potential cause-and-effects on population responses are more immediate than in the Kittiwake ANS case, which should in principle allow greater confidence in the approaches used to calculate the scaling of these actions. For example, in the case of predator exclusion, effects on survival and productivity of breeding birds are likely to be immediate, thereby removing the uncertainty that surrounds the timeline to the achievement of surplus production in ANS.

Imperfect knowledge makes monitoring a crucial part of implementing compensation measures, as in many cases only the compensation measure itself provides an opportunity to assess whether and to what extent compensation is effective. Monitoring requirements in all cases are therefore similar to those recommended for the Kittiwake ANS case discussed in detail above, and in principle should focus on two key aspects: (i) to document whether the direct effects of the compensation measure are achieved to the desired extent (e.g. fencing successfully excludes predators) and (ii) to monitor the response of the affected SPA features through population monitoring and/or specific monitoring of the demographic parameters which are thought to mediate the effect of the compensation measure on population dynamics. As a general principle, monitoring of compensation measures should not occur in isolation, but feed back into the relevant national monitoring schemes for the species of interest.

Consenting compensation measures in the face of imperfect knowledge also means that legal and practical frameworks should be in place to allow adaptive management processes to adjust the scale and/or type of compensation where monitoring proves that compensation measures are less successful than required.

5. Summary and recommendations

Our literature review identified little existing evidence to inform the mechanisms that would allow ANS provision to function as a compensation measure for Kittiwake mortality at OWFs, particularly when following a new colony approach. The proposed number of nest spaces at consented and proposed ANS across the reviewed OWFs comprises 5.76–9.87% of the total Kittiwake population in England, or 9.22–15.8% of the FFC SPA population, thereby raising the potential of significant impacts on regional metapopulation dynamics. The new colony approach fundamentally relies on the assumption that birds breeding at the ANS would not have bred elsewhere, which in turn implies there being a substantial existing pool of non-breeders who are not recruiting into the metapopulation because they are limited by available nest sites. While there is disagreement about the exact peak population size in the region (Coulson 2011), the available evidence indicates that the English population has been declining since the 1990s, albeit at a slower rate than populations elsewhere in the North Sea and North-east Atlantic. This casts doubt on nest site availability as the sole or primary limiting factor.

However, there is also significant uncertainty surrounding the demographic parameters used in these compensation figures, including the relative difference in breeding productivity between the ANS and the SPA. Assessment of the compensation target against a counterfactual, which the surplus approach aims to do, is therefore difficult to accurately estimate in lieu of ANS monitoring. Further, the OWFs that followed a surplus bird approach did not consider dispersal rates, resulting in the lowest compensation scaling magnitude for the Norfolk Projects (Table 2). Because this approach assumes that all surplus recruits produced at the ANS count towards the compensation target (instead of just the dispersing recruits), this shows that even a surplus bird approach could overestimate the compensation potential of the ANS if the subsequent breeding success of juveniles dispersing away from the ANS is lower than at the ANS.

Uncertainty surrounding demographic parameters may also lead to large uncertainty regarding the estimated timescale for mortality payback, i.e. the amount of time before the number of accumulated recruits produced at an ANS exceeds accumulated mortality. Depending on the assumed value of these demographic parameters, estimated timescales for payback could vary on the order of decades, leading to uncertainty over whether or not a given ANS could achieve compensation over the duration of its lifespan.

We recommend that a consistent and robust approach be used for future OWF applications taking these considerations into account. Based on our review, we recommend an approach conceptually similar to that adopted by Hornsea 3, but framed as a matrix population model (as in the MetaKitti project) with parameter constraints that would be required to ensure the ANS will be self-sustaining. The constraints make this approach a 'surplus bird' approach, which we consider important based on the precautionary principle, while allowing for separate estimates of dispersing birds – or at least the potential of dispersing birds. An appropriate population model should be used to determine the maximum values of breeding productivity and net dispersal used in the compensation calculations (see Appendix 3). Monitoring should be employed to assess whether the parameter values required for the ANS to be self-sustaining are realised, with adaptive management strategies utilised if the observed demographic rates are evidenced to significantly diverge from those assumed in the compensation calculations.

As with all reviewed methods, the recommended approach is sensitive to the choice of demographic parameters, which imposes uncertainty given the general lack of robust evidence about demographic performance of ANS. In the absence of robust data needed to evaluate the efficacy of ANS as a compensation measure, we recommend that extensive monitoring should be an essential requirement of ANS provision. The initial monitoring priority should be to ascertain rates and extent of ANS colonisation and breeding productivity, both of which can be achieved by count surveys comparable to the SMP protocol during the breeding season. Such monitoring data are critical to indicate whether or not ANS ultimately achieves breeding productivity required for a self-sustaining population, which is essential to ensure that ANS do not function as population sinks or ecological traps with a net negative impact on the existing metapopulation. It is crucial that ANS monitoring data be shared with national monitoring programmes such as SMP to facilitate assessment of the impact of ANS provision on Kittiwake metapopulation dynamics, and to determine whether ANS provision has a net positive or negative impact.

We also recommend that results should be made fully transparent and reproducible, and made available to stakeholders. Methods should be constructed in a way that is insensitive to software choice. It is important to provide an unambiguous model description and parameter definitions to provide the transparency needed for others to repeat the models in same or different software, while allowing further tests of the model's implementation correctness and sensitivity to the particular parameter values adopted in the model.

Specifically, we recommend the following:

1. Compensation calculations should explicitly model the annual share of recruits that can disperse back into the SPA network to compensate for the collision mortality (conceptually similar to the Hornsea 3 approach), but with an explicit constraint that the ANS must be self-sustaining. This includes:

    a. modelling a staggered entry into the breeding population from age three;

    b. use of the maximum breeding productivity out of the estimated SPA breeding productivity or that required for the ANS to be self-sustaining (as determined by an appropriate population model);

    c. estimates of potential maximum rates of net dispersal conditional on a self-sustaining ANS population (as determined by an appropriate population model).

2. Monitoring at the ANS is essential and should incorporate, at a minimum:

    a. colonisation monitoring during establishment, including distinguishing counts of prospecting from breeding birds;

    b. breeding population counts over the lifetime of the ANS;

    c. productivity monitoring over the lifetime of the ANS;

    d. colour ringing of chicks at accessible sites until philopatric recruitment can be confirmed (i.e. likely a minimum of 10 years);

    e. regular ring resighting effort at the ANS and nearby colonies;

    f. data sharing with national monitoring programmes such as SMP. This is critical, especially given the consented and proposed scale of ANS provisioning structures;

    g. desirable: Baseline monitoring at neighbouring existing colonies both prior to ANS construction and during ANS operation to establish temporal and spatial variation in demographic rates as well as possible impacts of the ANS itself.

3. Adaptive management: consenting compensation measures in the face of imperfect knowledge also means that legal and practical frameworks should be in place to allow adaptive management processes to adjust the scale and/or type of compensation where monitoring proves that compensation measures perform differently than anticipated. In particular, adaptive management

measures should ensure that any mortality debt incurred during the colonisation phase of the ANS is sufficiently compensated over the lifetime of the ANS.

4. Compensation calculations should be made fully transparent and reproducible, and conducted in a way that is insensitive to software choice.

We adapted a population model from Horswill et al. (2022) to encompass the features outlined above and calculated compensation population sizes for the reviewed OWF developments at the ANS productivity estimates used across projects. Model and computational details of the recommended approach are provided in Appendix 3. Estimated compensation population sizes are provided in Table 5. Compensation population sizes were sensitive to assumed demographic parameters such as the assumed ANS productivity, and were on the same order of magnitude but generally somewhat larger than existing estimates, particularly for ANS productivities close to the regional average.

Table 5: Recalculated compensation population sizes for the reviewed OWF developments using three different assumed ANS productivity levels as employed across different projects. First-year and adult survival rates were identical across all re-calculations at 0.79 and 0.854, respectively. Ratio = compensation ratio.

OWF	Compensation target (mortalities/yr)	Consented / proposed compensation population (pairs)		Recalculated compensation population (excl. ratio; pairs)		
		excl. ratio	incl. ratio	F=0.819	F=1.0	F=1.2
Hornsea 3	73	467	467	643	360	247
Norfolk Boreas	14	47	145	124	69	48
Norfolk Vanguard	21	71	215	185	104	71
East Anglia 1N	2	20	60	18	10	7
East Anglia 2	2	20	60	18	10	7
Hornsea 4	43	115	230	379	212	146
SEP & DEP	17	68	68	150	84	58
Round 4	338	1,872	1,872	2,974	1,664	1,143

Although there is currently little empirical evidence relating to the efficacy of ANS as a conservation measure, increased renewable energy provision forms a key UK strategy for combating climate change. OWF developments will therefore continue to increase in number and effective compensation measures for impacts to seabird features of SPAs will become more pertinent. We therefore stress the need for comprehensive monitoring to collect the data required to evaluate the efficacy of ANS as a compensation measure. Our recommendations above should ensure that these data are available in the future, whilst ensuring that calculation of compensation populations is as robust as possible given the current data limitations.

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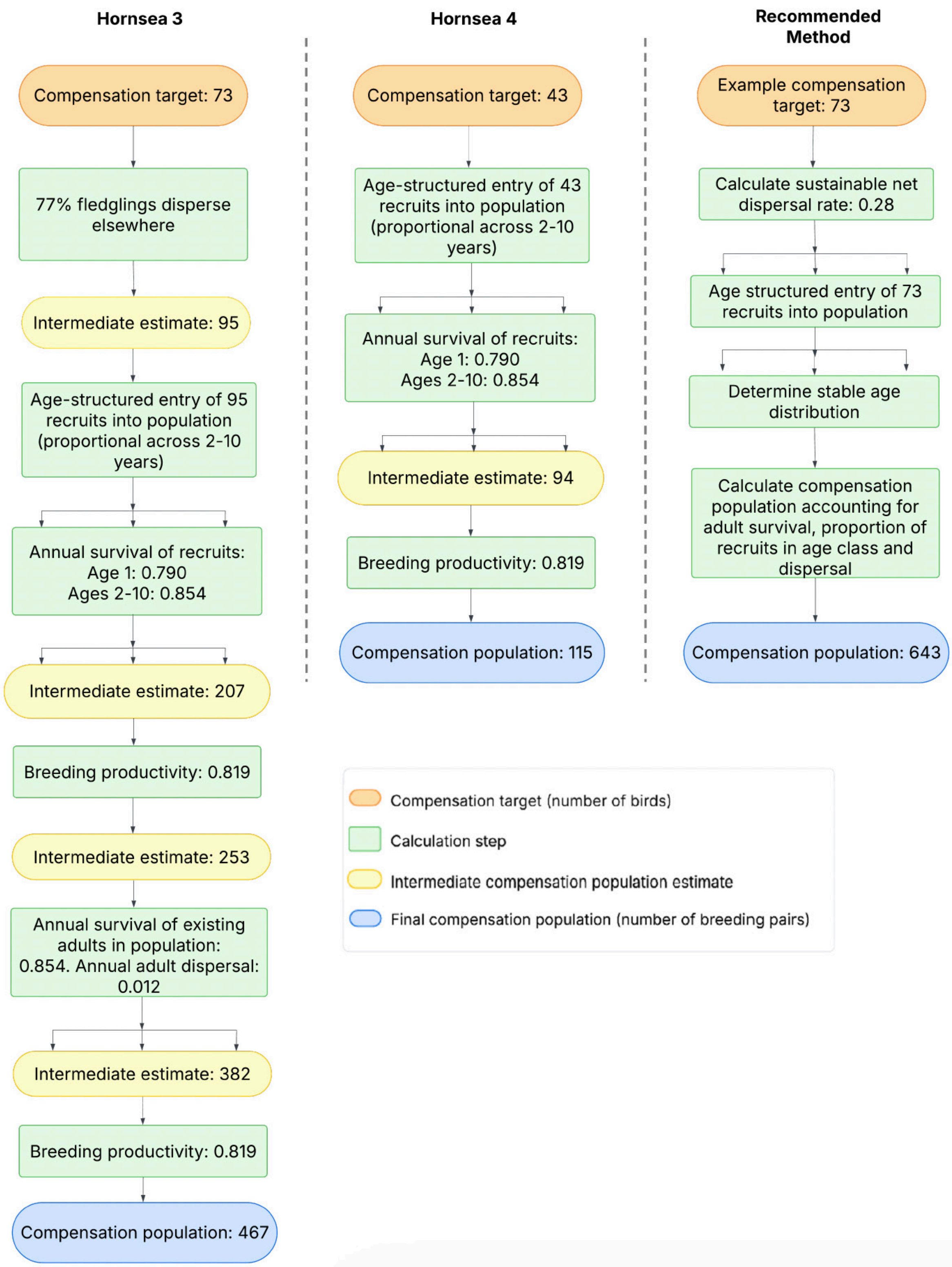
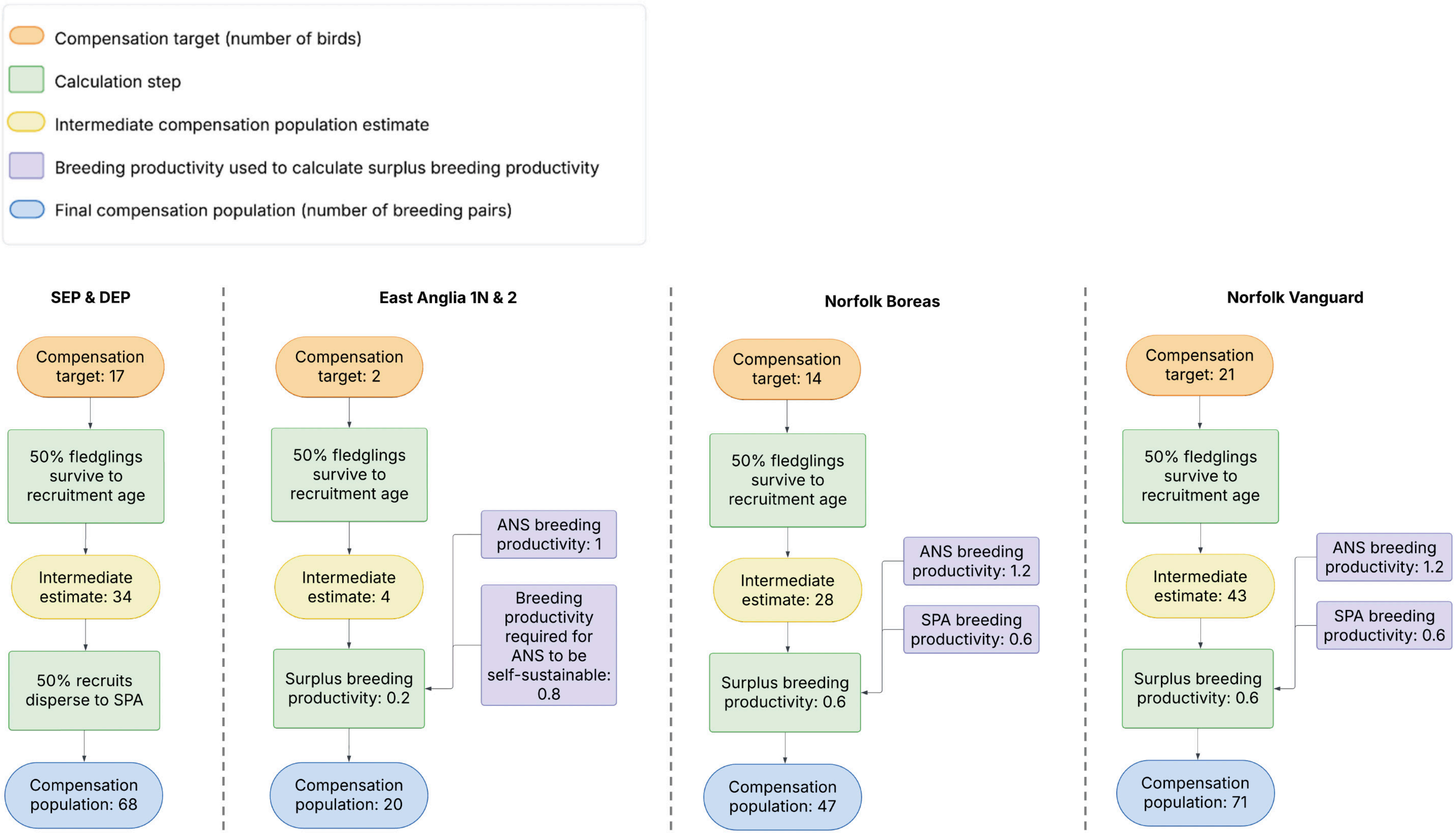
Appendix 1: Visualisation of methods for calculating the compensation population




Compensation target (number of birds)
Calculation step
Intermediate compensation population estimate
Breeding productivity used to calculate surplus breeding productivity
Final compensation population (number of breeding pairs)
SEP & DEP
Compensation target: 17
50% fledglings survive to recruitment age
Intermediate estimate: 34
50% recruits disperse to SPA
Compensation population: 68
East Anglia 1N & 2
Compensation target: 2
50% fledglings survive to recruitment age
Intermediate estimate: 4
ANS breeding productivity: 1
Breeding productivity required for ANS to be self-sustainable: 0.8
Surplus breeding productivity: 0.2
Compensation population: 20
Norfolk Boreas
Compensation target: 14
50% fledglings survive to recruitment age
Intermediate estimate: 28
ANS breeding productivity: 1.2
SPA breeding productivity: 0.6
Surplus breeding productivity: 0.6
Compensation population: 47
Norfolk Vanguard
Compensation target: 21
50% fledglings survive to recruitment age
Intermediate estimate: 43
ANS breeding productivity: 1.2
SPA breeding productivity: 0.6
Surplus breeding productivity: 0.6
Compensation population: 71

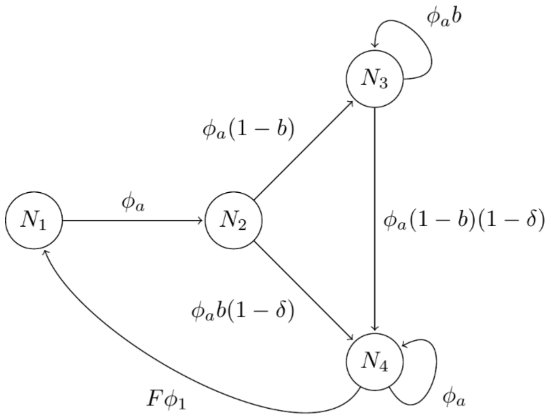
Appendix 2: Assessment of sustainable net dispersal rates of recruits

Natal philopatry at an individual colony can be assessed in two ways, either by considering a cohort of young where the number of individuals that eventually returned to breed in their natal colony is expressed as a proportion of the total that have survived and bred anywhere (definition used by Horswill & Robinson 2015), or by relating the number of philopatric recruits in a colony to the total number of new recruits to that colony over the same period of time (i.e. philopatry plus immigration; this definition was used by Coulson & Coulson 2008). Both approaches necessitate assumptions about survival rates of both potential recruits and existing breeders and are therefore liable to be biased. It is thought that the two approaches give similar estimates, but this is not guaranteed, especially for colonies that are strongly growing or declining (Coulson & Coulson 2008). Natal dispersal is the complement of natal philopatry, i.e. the sum of both rates must equal 1, and thus can be defined analogously. The secondary literature generally does not distinguish between the two definitions, so determining the provenance of available estimates of natal dispersal can be challenging. However, in the Kittiwake system, neither definition can be interpreted as a measure of net emigration, given that natal dispersal is generally compensated to some degree by recruitment of immigrant birds fledged from other colonies.

To estimate sustainable levels of net dispersal we utilised a simplified version of the population model conceptually underpinning the Hornsea 3 approach. This model also allows for a staggered entry of birds into the breeding population but uses the structured population modelling approach of Horswill et al. (2022) where birds enter the breeding population between age three and age five years. Compared to the Hornsea 3 approach where birds may enter the breeding population between ages 1–10 years, the Horswill et al. (2022) approach is simpler (and therefore easier to implement) and is less reliant on estimated parameters from a single colony. We used a pre-breeding census parameterisation for the projection matrix A_i (Caswell 2001) with four life stages and the same transition probabilities as employed by the Hornsea 3 approach, i.e. first year survival (ϕ_1=0.79), adult survival (ϕ_a=0.854) and productivity (*F*=0.819). The model allowed a fraction *b*=0.25 of two year olds to enter the breeding class, with (*1–b*) of the cohort moving to a pre-breeding class. From the pre-breeding class a fraction b remain pre-breeders while (*1–b*) enter the breeding class. Additionally, a fraction of δ individuals dispersed away from the population upon the transition into the breeding class. This parameter can be used to describe net dispersal out of the ANS population. We assumed a 1:1 sex ratio in the population and halved fecundity to model female numbers only.

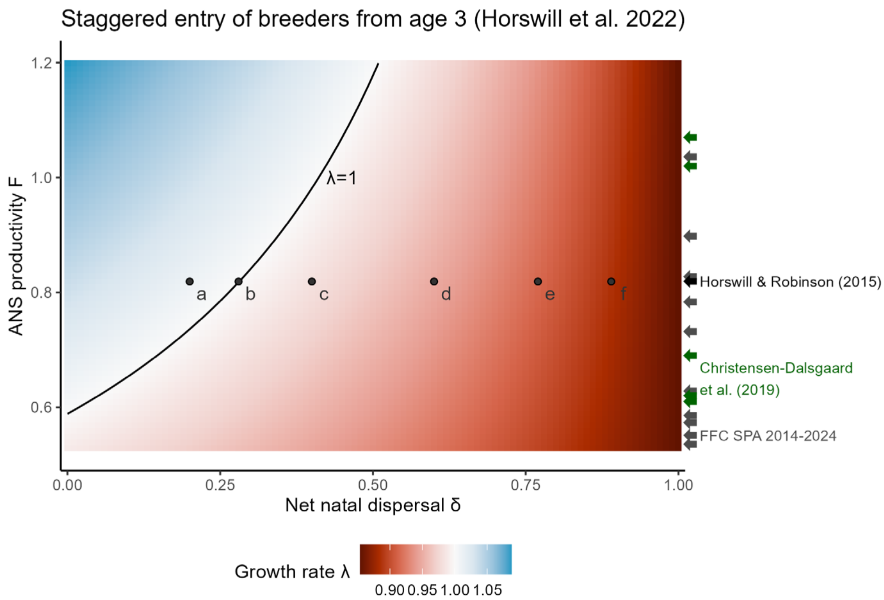
$$A_i = \begin{pmatrix} 0 & 0 & 0 & \phi_1 \frac{F}{2} \\ \phi_a & 0 & 0 & 0 \\ 0 & \phi_a(1-b) & \phi_a b & 0 \\ 0 & \phi_a b(1-\delta) & \phi_a(1-b)(1-\delta) & \phi_a \end{pmatrix}$$

Figure A: Life-cycle diagram representing the state process equations summarised in the transition matrix A describing kittiwake population dynamic. Birds reach age 1 year (N_1) with probability $F\phi_1$, and age 2 years (N_2) with probability ϕ_a . At age two, 75% (1–*b*) of individuals move to the third (pre-breeding) class (N_3) and 25% (*b*) of individuals enter the breeding class (N_4) at rate (1–δ) or disperse at rate δ. From the third class, 25% (*b*) of individuals remain as pre-breeders and 75% (1–*b*) become breeders (N_4) at rate (1-δ) or disperse at rate δ. After age 1, individuals have a survival probability equivalent to that of adults (ϕ_a).



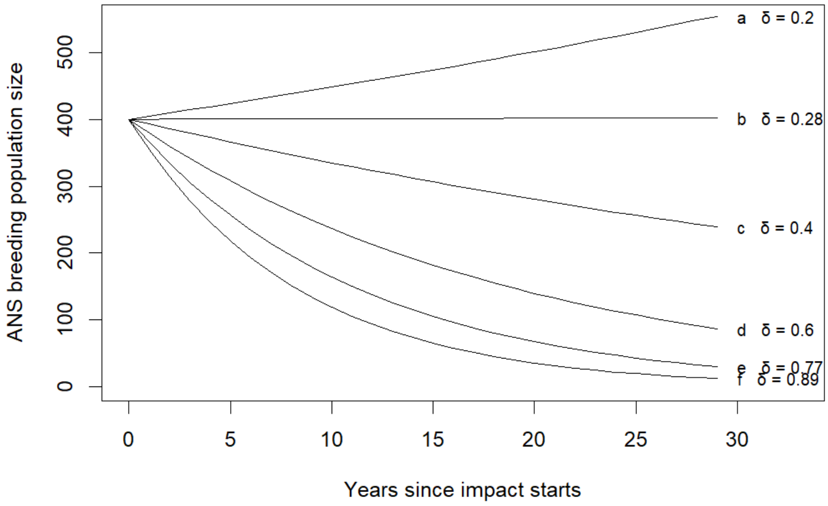
To estimate achievable rates of net dispersal δ we calculated asymptotic growth rates λ for this population model for a range of productivity and net dispersal rates. Combinations of these parameters that yielded a stable or growing population (λ ≥ 1) were deemed to be permissible as input parameters for estimating compensation population sizes under what is effectively a surplus bird approach.

Figure B: Realised population growth rates λ for an ANS population for different levels of productivity and net natal dispersal (using first year and adult survival rates of 0.79 and 0.854, respectively). Blue shades indicate a growing population at the ANS (λ > 1), red shades indicate a declining ANS population (λ < 1) and hence unsustainable levels of dispersal. The black line indicates combinations of productivity and dispersal leading to a stable population. Dark symbols a-f show a selection of different dispersal rates (a=0.2, b=0.28, c=0.4, d=0.6, e=0.77, f=0.89. b is the maximum sustainable dispersal at F=0.819; e,f are the dispersal rates assumed in Hornsea 3 approach) at the productivity assumed in the Hornsea 3 approach. Corresponding population trajectories are illustrated in Figure C. Arrows on the right margin show observed productivities in different locations. Black: average productivity in the East Region (Horswill & Robinson 2015). Green: Annual productivity values for individual oil rigs in Northwest North Sea (Christensen-Dalsgaard et al. 2019). Grey: Annual productivity values at FFC SPA 2014–2024 (SMP database).



We found that realistic productivity values (F = 0.6–1.2) constrained net dispersal rates at which the ANS remained self-sustaining to c. 0–0.5 at the assumed survival rates. This range of productivity levels includes the East region average of Horswill & Robinson (2015) (0.819), as well as observed productivities at offshore structures in the north-west North Sea (Christensen-Daalsgard et al. 2019), and most – but not all – of the annual productivities observed at FFC SPA (Figure B). We further found that the productivity level assumed in the Hornsea 3 approach (F=0.819; Horswill & Robinson 2015) was expected to yield a growing ANS population when treated as a closed system (i.e. no dispersal), but that this productivity level was not able to support the assumed levels of dispersal (0.77 and 0.89, respectively, Figures B(e,f) and C(e,f)). The maximum sustainable dispersal at this level of productivity was 0.28 (Figures B(b) and C(b)).

Figure C: Realised population dynamics of a hypothetical ANS with 400 breeding pairs in year 1 at different levels of net natal dispersal δ (using first year and adult survival rates ϕ of 0.79 and 0.854, respectively and a productivity of F=0.819). a–f show a selection of different dispersal rates (b is the maximum sustainable dispersal at F=0.819; e,f are the dispersal rates assumed in Hornsea 3 approach).



R code for the simulation approach:

```
# load required packages
library(dplyr) # for data manipulation
library(popbio) # for population model calculations
library(ggplot2) # for plotting
library(colorspace) # for plotting
library(metR) # for plotting
library(shadowtext) # for plotting

#  demographic parameters
AP <-0.854       # average adult survival (Horswill & Robinson 2015)
JP <-0.79        # first year survival (Horswill & Robinson 2015)
FEC<-0.819       # average fecundity from Hornsea 3 NB - this does not mat
ch table 3
b<-0.25          # proportion of birds that start breeding at age 3 years
from Horswill et al. 2022

fecs = seq(0.599,1.2, by = 0.01) # range of fecundities to simulate
```

```r
disps = seq(0,1,by=0.01) # range of net dispersal rates to simulate

scens2 = expand.grid(fec = fecs, disp = disps) # create all combinations o
f the above
scens2$lambda = NA_real_ # add an empty column for growth rate estimates

#iterate over all fecundity and dispersal scenarios
for (i in 1:nrow(scens2)){

#projection matrix for staggered entry model with dispersal of recruits
A<-matrix(c(0,0,0,scens2$fec[i]/2*JP,
            AP,0,0,0,
            0,AP*(1-b),AP*b,0,
            0,AP*b*(1-scens2$disp[i]),AP*(1-b)*(1-scens2$disp[i]),AP),4,4,
byrow=T)

# Calculate asymptotic estimates of growth rates and stable age distributi
on
eigen_analysis <- eigen.analysis(A)

#collect growth rate estimate
scens2$lambda[i] <- eigen_analysis$lambda1
}

#extract maximum net dispersal rate for stable population and given fecund
ity
max_dispersal_scenario = filter(scens2, fec == FEC & lambda >= 1) %>% filt
er(disp ==max(disp))
max_dispersal_scenario

##     fec disp   lambda
## 1 0.819 0.28 1.000157

#plot simulation results
ggplot(scens2, aes(x=disp,y=fec,fill=lambda, z=lambda)) +
  geom_tile() +
  scale_fill_continuous_divergingx(palette = 'RdBu', mid = 1) +
  geom_contour(breaks = 1, col = 'black') + geom_point(aes(x=0.77, y=0.819
), pch=21, fill = 'white') +
  geom_point(aes(x=0.89, y=0.819), pch=21, fill = 'white') +
  geom_point(data = max_dispersal_scenario) +
  ggtitle('Staggered entry of breeders from age 3 (Horswill et al. 2022)')
+
  annotate('text', x=.45, y = 1, label = 'λ=1',) +
  annotate('shadowtext', x=.83, y = .79, label = 'Hornsea 3 scenarios') +
  annotate('shadowtext', x=max_dispersal_scenario$disp+0.03, y = max_dispe
rsal_scenario$fec, label = paste0('max. dispersal\nat F=',max_dispersal_sc
enario$fec), hjust = 0) +
  ylab('Productivity') +
  xlab('Net natal dispersal') +
  theme_classic()
```

Appendix 3: Computational details of the recommended approach for calculating compensation scale

We recommend that calculations of the size of the compensation population are based on a structured population model to ensure that selected combinations of demographic parameters are constrained to those that yield a net addition of recruits into the metapopulation, while at the same time falling into realistically achievable parameter ranges (c.f. Appendix 2, Figure B). This mirrors approaches taken in other wind energy related contexts (e.g. Fielding & Haworth 2010, Millsap et al. 2022). We note that the current evidence base for what constitutes a realistically achievable demographic parameter value is limited, given the scarcity of observational data from birds breeding on offshore structures in the Southern North Sea. Adaptive management actions and/or updated recommendations about suitable demographic parameter ranges may be required as such information becomes available.

Here we use a population model that employs an age-structure following Horswill et al. (2022), which can be considered a simplified version of the age structure underpinning the Hornsea 3 approach. In addition, we explicitly model dispersal between the ANS and the metapopulation.

The objective of the calculation is to find the minimum size of the breeding population required to produce a number of annual recruits into the breeding class that equals or exceeds the estimated collision mortality.

We implemented the population model in the software package R (R Core Team 2024) and calculated asymptotic properties using functions from the popbio package (Stubben & Milligan 2007), as per Appendix 2. However, our results should be insensitive to software choices — within the limits of numerical precision — as population models are built around the same underlying mathematics. It is also important to note that population models are approximations of the biological dynamics and — as outlined in the main text — there is usually insufficient information on parameter values to justify anything other than relatively simple projection matrices. It is therefore more important to provide an unambiguous model description and parameter definitions to provide the transparency needed for others to repeat the models in same or different software, while allowing further tests of the model's sensitivity to the particular parameter values adopted in the model.

The calculation proceeds in the following steps:

Step 1:

Select appropriate values for survival φ_i, productivity F, and recruitment probability b (i.e. proportion of birds that begin breeding at a particular age class). Here we use the same survival and productivity rates as in the Hornsea 3 approach, and a recruitment probability of 25% for three-year old birds and 75% for non-breeders in subsequent age classes (following Horswill et al., 2022).

Step 2:

Estimate maximum sustainable net dispersal rate δ which allows the asymptotic population growth rate λ to remain equal or larger than 1. We used the *eigen.analysis* function in *popbio* for this purpose, as per Appendix 2.

Step 3:

Determine the stable age structure for the projection matrix using the maximised value for the net dispersal rate δ. We used the *eigen.analysis* function in *popbio* for this purpose.

The stable age distribution is a vector of proportions which we designate $p=\{p_1, p_2, p_3, p_4\}$ where p_i designates the proportion of individuals in stage i of the population.

Step 4:

The compensation population, i.e. the required breeding population size P (in breeding pairs) to compensate a predetermined annual mortality M (specified as individuals across both sexes) – effectively an annual harvest – is then calculated as

$$P = \frac{M}{2 \times (p_2 \varphi_a b\delta + \ p_3 \varphi_a (1-b)\delta)} \times p_4$$

Where the factor 2 accounts for the fact that the model considers female offspring only, $p_2 \varphi_a b\delta$ describes the surviving individuals recruiting from N_2 into the dispersing breeder class, $p_3 \varphi_a (1-b)\delta$ describes the surviving individuals recruiting from N_3 into the dispersing breeder class, and p_4 describes the proportion of breeders in the ANS population.

Example R code for the calculations is available at **https://doi.org/10.5281/zenodo.17474589**

Cover images: Kittiwakes, by Sam Langlois / BTO

Review of methods used to calculate scale of artificial nesting structures proposed as a compensation measure for Kittiwake mortality at offshore wind farms

Artificial Nest Structures (ANSs) have been approved as strategic compensation measures following derogation cases required to enable the consent of several offshore wind farms due to concerns about negative impacts on seabird features of designated Special Protection Areas (SPAs). However, there is stakeholder disagreement regarding the efficacy of such compensation measures and the methods used to calculate their required scale, i.e. the number of breeding Kittiwake pairs needed to occupy the site to produce the number of new breeding birds required to compensate the predicted mortality impact.

This report reviews the suitability of methods used to calculate the scale of ANSs provided as compensation measures for Kittiwake mortality at offshore wind farms in English waters, due to turbine collision only.

Suggested citation: Rhoades, J., Johnston, D.T., Humphreys, E.M. & Boersch-Supan, P.H. 2025. Review of methods used to calculate scale of artificial nesting structures proposed as a compensation measure for Kittiwake mortality at offshore wind farms. *BTO Research Report* **778**, BTO, Thetford, UK.

ISBN 978-1-912642-84-7

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