

Volume 2: Appendices

Appendix 9

NISA Bioenergetic Modelling



Harbour porpoise bioenergetic modelling

The potential effect of disturbance from pile driving noise on harbour porpoise as a feature of the Rockabill to Dalkey Island SAC, the Lambay Island SAC and the Codling Fault Zone SAC

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Introduction

Given the close proximity of the proposed North Irish Sea Array (NISA) Offshore Wind Farm (hereafter referred to as the 'proposed development') to the Rockabill to Dalkey Island Special Area of Conservation (SAC), the Lambay Island SAC and the Codling Fault Zone SAC, it is necessary for the Natura Impact Statement (NIS) to consider potential impacts to harbour porpoise within these protected sites. The objective of this document is to support the Appropriate Assessment, and focusses on the potential for disturbance resulting from underwater noise from pile driving activities to impact on the harbour porpoise feature of the SACs.

Conservation Objectives

The conservation objectives for the Rockabill to Dalkey Island SAC for harbour porpoise (site code: 3000) are to maintain the favourable conservation condition of harbour porpoise in the SAC. Under this, Target 2 relates to disturbance from underwater noise:

- Target 2: Human activities should occur at levels that do not adversely affect the harbour porpoise community at the site.
 - *Proposed activities or operations should not introduce man-made energy (e.g. aerial or underwater noise, light or thermal energy) at levels that could result in a significant negative impact on individuals and/or the community of harbour porpoise within the site. This refers to the aquatic habitats used by the species in addition to important natural behaviours during the species annual cycle.*

At the time of writing, there are no Conservation Objectives for harbour porpoise at the Lambay Island SAC or the Codling Fault Zone SAC.

The marine mammal impact assessment (Section 5, NIS) does identify the potential for disturbance to harbour porpoise from pile driving activities. Given the close proximity of the proposed development to the Rockabill to Dalkey Island SAC, the Lambay Island SAC and the Codling Fault Zone SAC, it is predicted that some individuals that use the SACs may be disturbed. This disturbance effect may result in a temporary change in the distribution of individuals using the SACs, and a temporary change in behaviour whereby individual porpoise may cease foraging for a limited period of time.



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Use of bioenergetic modelling for conservation

Disturbance from pile driving activities has the potential to cause behavioural, physiological and health changes which can have subsequent effects on an individual's vital rates (i.e. their chances of reproducing or surviving). The effects of disturbance from pile driving on animals are widely considered to be mediated by two factors:

- 1) the state of the individual (e.g., life history stage (e.g. juvenile, adult), exposure history, body condition (a proxy for overall health)), and
- 2) the environment that the animals live in (e.g. prey resource availability).

Dynamic bioenergetic models can be used to predict the changes in individual body condition and explore how such changes could affect that individual's vital rates. These kinds of models have been widely used to investigate how natural and anthropogenic disturbance might affect individuals and populations of marine mammals (see Pirodda et al. (2018) and Pirodda et al. (2023) for reviews).

A benefit of these bioenergetics models is that they can be used to take into account how an individual's energetic requirements vary during different life history stages (e.g. calves, juveniles and adults) and take into account the state of the environment the individual is in (e.g., different quality of environment, presence of predators). Therefore, these models provide a useful method to consider how disturbance can affect different life stages under different assumptions about the quality of the environment. It's important to note that animals in a good quality environment (or condition) are likely to be more resilient to lost foraging opportunities than those in a poor environment (or condition).

Estimating the effect of disturbance from pile driving on harbour porpoises

The impact of disturbance on porpoises will depend on:

- 1) the "**probability of disturbance**": this is informed by the probability that an individual is exposed to noise associated with that activity ("**probability of exposure**") and the probability that it will respond to that exposure ("**probability of response**") and
- 2) The "**disturbance effect**": how long that individual ceases to feed as a result of its response.

Within the bioenergetic model, the product of the **probability of exposure** and the **probability of response** acts as a single parameter (an index), referred to as "**probability of disturbance**". For highly mobile species it is expected that the probability of disturbance would be close to 0 whereas values closer to 1 are expected for species with a high degree of residency in the impacted area where all animals are disturbed on every disturbance day¹. The unit for the disturbance effect is the number of hours that animals cease foraging for, following disturbance.

Understanding the extent to which porpoises might be disturbed requires consideration of the current state of knowledge regarding their movement and foraging behaviour and the effects of

¹ The residency patterns of harbour porpoise in the Rockabill and Dalkey Island SAC is unknown. While studies have shown that porpoise are present year round, it is not known if the porpoise present are resident or transient in the area. Berrow et al. (2021) reported a 46% decline in density estimates within the SAC in 2021 compared to the survey in 2016. They comment that it is "*more likely a change in the local distribution of porpoises, adjacent to the SAC [...]. Small changes in local distribution, driven by the distribution of their preferred prey can have profound effects on density estimates within a relatively small SAC compared to individual's home range*".



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disturbance (as these factors, in combination, dictate the likelihood of exposure, disturbance and effect). Therefore, to ensure bioenergetic model simulations are robust, detail on the current state of knowledge regarding harbour porpoises (regarding probability of exposure, probability of response and disturbance effect) is provided, in the context of the assessment herein.

Probability of exposure

The main source of data from which harbour porpoise movement ecology is understood is animal-borne telemetry (i.e. tags which track the locations of animals over time). Tags have been deployed on harbour porpoises for decades, with deployments ranging from hours (Wisniewska et al. 2016, Wisniewska et al. 2018) to over a year (Nielsen et al. 2018). To date, porpoises have been tagged in a few locations globally (the waters off Greenland, the Inner Danish waters (Kattegat & Skagerrak) and off the east coast of the USA and Canada). These studies have generated key data improving our understanding of the species movement ecology. Harbour porpoises are generally considered to be highly mobile, ranging over large distances – but sometimes utilising smaller core regions, for short periods (e.g. weeks). Estimated mean daily movements in the Bay of Fundy were between ~14 and 59 km per day.

Nielsen et al. (2018) demonstrated the long-term (i.e. months-years) large-scale movements of harbour porpoises using satellite telemetry data from West Greenland and Danish waters. Porpoises tagged, generally with shorter deployment durations, in inner Danish waters were observed to stay mostly within shallower waters of the Kattegat and Skagerrak, but with some individuals ranging over the continental shelf and into the North Sea (Nabe-Nielsen et al. 2018) (Nielsen et al. 2018). One animal in this temporally restricted dataset did travel 1,000 km from the tagging location to the waters off Shetland in the span of a few days (Teilmann et al. 2008). Animals tagged in the waters between Greenland and Canada demonstrated large-scale ranging with movements of 1,000 km offshore (and into waters >2,500 m deep). Of the 30 animals tagged, ~75% moved offshore (i.e. 1,000s km away). All the tagged porpoises exhibited strong site fidelity returning to the same general area after moving offshore into the Atlantic Ocean basin. The authors note: *“Six tags from Greenland transmitted long enough (up to 3 yr) to demonstrate extensive movements and strong site fidelity to the tagging site in West Greenland the following summer. This study documents that harbour porpoises use oceanic habitats and can dive to depths that enable mesopelagic foraging, while repeatedly demonstrating summer site fidelity to coastal areas”*. This work raises a question of whether the movement behaviour of North Sea porpoises has been adequately captured by shorter tag deployments in Inner Danish waters studies (a region which is considered to maintain a relatively closed population – i.e. one with limited movements).

In terms of the spatial and temporal area usage observed in porpoises, animals tagged in the Bay of Fundy, Canada (for 2-5 month deployments) occupied focal regions for periods of days to months (112 – 415 km²), while also occasionally using greater, expanded ranges (4,728 – 22,103 km²) (Johnston et al. 2005). Animals tagged in an earlier study in the same region estimated porpoises were using a range of ~50,000 km² (Read and Westgate 1997). Teilmann et al. (2008) indicated some similarities to the work in Canada with short-term focal regions of between 400 km² and 1,600 km².

The Rockabill to Dalkey Island SAC is 273 km² in surface area. Based on the current state of knowledge it is highly likely that porpoises are using this area periodically and that it represents a small part of a larger range.

Chudzińska et al. (2024) used a detailed harbour porpoise movement model (DEPONS) to estimate how the probability of exposure changed for different high- and low-use areas for a semi-resident population in Inner Danish waters. This is a region that is 40 km wide at its northern end and 110 km wide at the southern end (its widest point) – which topographically might be considered comparable



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to the Irish Sea (34 km wide and 74 km respectively; though 200 km wide in the middle). Chudzińska et al. (2024) explored how the probability of exposure varied under different scenarios where the impacted area had a radius of 30 km (corresponding to an area of 2,826 km²). The high-use area estimates are considered as a proxy for a region close to an SAC, following Chudzińska et al. (2024) where 75% of simulated harbour porpoise in a **high-use area had a probability of exposure in the range 0.15-0.35 (mean 0.24)**. For the **low-use area the mean probability of exposure estimates were <0.1**. All estimates are for a semi-resident population in the Inner Danish waters and, whilst there is no information on how harbour porpoise use the Irish and Celtic Seas, using the “high use” estimate from that region represents a realistic, but conservative estimate given the timescales associated with construction (i.e. many months). If values from the North Sea DEPONS model were used – **all probability of exposure values would be close to 0** (due to the expansive modelled movement of animals in that region).

Probability of response

The probability of response is likely to vary with distance from the source of disturbance (Graham et al. 2019) and potentially due to the state of the animal (e.g. life stage, body condition, past experience etc.) (Graham et al. 2019). A mean **probability of response** can be calculated from dose-response relationships (such as Figure 6 of Graham et al. (2019) for harbour porpoise in the vicinity of the Beatrice Offshore Windfarm during its construction). A mean probability of response was calculated based on the dose-response relationship in combination with the approach described by Tyack and Thomas (2019). This resulted in a **mean probability of response of 0.23 for harbour porpoise within 30 km of the piling activity**.

Probability of disturbance

To determine the potential effects on vital rates, it is possible to multiply the **mean probability of exposure** (0.24) by the **mean probability of response** (0.23) to obtain a **probability of disturbance** value of 0.05. Therefore, if porpoise movements in the Irish and Celtic Sea are analogous to those in the Inner Danish waters DEPONS movement model (a potentially conservative assumption), then **the probability of disturbance is likely to be <0.05**.

If the upper bound of the **probability of exposure** is used (0.35) then this can be multiplied by the **mean probability of response** (0.23) to obtain a **probability of disturbance value of 0.08**. Critically, based on the available data and modelling tools, there is **very little scientific support for probability of disturbance values of above 0.1**.

Disturbance effect

Above discusses the current state of knowledge which informs the likelihood that an animal will be present to be disturbed by a single noise source. Now it is important to consider what is known about how exposure to low frequency broadband noise, like that generated during pile driving, affects foraging of harbour porpoises (and, therefore, energy intake and expenditure). Currently, there is relatively little data to describe porpoise foraging behaviour and the effects of disturbance (in terms of the duration of disrupted foraging). However, consideration is given as to how to apply the current state of knowledge to provide estimates of this parameter.

To evaluate the likely duration of foraging disruptions, a range of observed harbour porpoise swim speeds (1.2, 2.0 and 3.0 ms⁻¹ (Verfuß et al. 2009, Kastelein et al. 2018)) and maximum disturbance distances were used (based on the spatial extent of responses from 2.2 -33 km summarised in Brandt et al. (2018); Southall et al. (2019); Brown et al. (2023)), assuming that while the animal is swimming from a starting location to a “safe distance” it is not foraging (Table 1). This suggests **very few animals would cease foraging for more than 6 hours and the vast majority would be disrupted for much less time** (Table 1). Following Benhemma-Le Gall et al. (2021), where at 11-12 km from the



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source there was no reduction in foraging probability this would suggest **impacted foraging durations of only 0.46 - 2.55 hours**.

Table 1 1Number of foraging hours lost (effect of disturbance) calculated from distance/observed swim speeds, where distance is the maximum disturbance distance - the animal's location in relation to the piling vessel at the start of piling.

Maximum disturbance distance											
6 km				12 km				36 km			
Distance from source (km)	Swim speed (ms ⁻¹)			Distance from source (km)	Swim speed (ms ⁻¹)			Distance from source (km)	Swim speed (ms ⁻¹)		
	1.2	2.0	3.0		1.2	2.0	3.0		1.2	2.0	3.0
	Lost foraging hours				Lost foraging hours				Lost foraging hours		
0.5	1.27	0.76	0.51	1	2.55	1.53	1.02	3	7.64	4.58	3.06
1	1.16	0.69	0.46	2	2.31	1.39	0.93	6	6.94	4.17	2.78
2	0.93	0.56	0.37	4	1.85	1.11	0.74	12	5.56	3.33	2.22
3	0.69	0.42	0.28	6	1.39	0.83	0.56	18	4.17	2.50	1.67
4	0.46	0.28	0.19	8	0.93	0.56	0.37	24	2.78	1.67	1.11
5	0.23	0.14	0.09	10	0.46	0.28	0.19	30	1.39	0.83	0.56

The current iPCoD model relies on transfer functions derived via expert elicitation in 2018. Following a review and discussion of the available scientific data and literature, experts agreed that when assessing the effects of a day of disturbance (i.e. a day upon which pile driving occurs), that the disrupted foraging was unlikely to exceed an average of 6 hours of lost foraging. Whilst this assessment was made in 2018, before Benhemma-Le Gall et al. (2021) published their work, this assumption appears reasonable, though is likely conservative.

Report intent

The purpose of this report is to investigate whether disturbance resulting from pile driving at the proposed development is likely to result in significant impacts to individual harbour porpoise vital rates (survival and reproduction).

Methods

The individual-based, dynamic bioenergetics model developed by Hin et al. (2019) for long-finned pilot whales was adapted so that it could be applied to harbour porpoise (HP). A full description of the bioenergetic models can be found in Harwood et al. (2020), Harwood et al. (2022) and Chudzińska et al. (2024). A range of simulations were then run, which differed by probability of disturbance and disturbance effect (in terms of lost foraging time). Below is a short, general description of the bioenergetic models, and the way in which uncertainty around model parameter values was addressed (see Appendix 1 and Chudzińska et al. (2024) for further details).

Dynamic bioenergetic model for harbour porpoise

Dynamic bioenergetic theory provides a mechanistic framework that predicts the consequences of an organism's acquisition of environmental resources (i.e. finding suitable prey) for growth, reproduction, and to survive. The models are called 'dynamic' as the energy acquisition and allocation varies in time depending on the animal's physiological state, energy demand and prey availability (Nisbet et al. 2000, Kooijman and Kooijman 2010). Thus, the models provide a tool to

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investigate interactions between populations and their resources, and how this link between animals and resources (availability and/or acquisition) can be affected by disturbance.

The bioenergetic model presented in this report tracks the way in which individual female harbour porpoises assimilate energy over the course of their lives from weaning to death, and how this energy is allocated to daily energy needs (i.e., field metabolism), growth, and the costs of reproduction (e.g., foetal development, and lactation). A simulated individual's energy needs vary depending on their current nutritional state and reproductive state and animals can gain and lose reserves depending on whether or not they obtain sufficient energy. Animals are assumed to starve if their energy levels get too low. Pregnancy is dictated by animal body condition (i.e., energy levels) and calves are considered to be entirely dependent on their mother. Calves are assumed to begin foraging before they wean as they get older.

Age-related and seasonal fluctuations in body condition are therefore the result of variations in the resource density (i.e. prey availability) experienced by individuals and their energy demands. Figure 1 shows the predicted changes in body condition of a typical adult female and her offspring over the course of three reproductive cycles (breeding seasons) in an undisturbed environment. The model proceeds in discrete time steps of 1 day, and each year consists of 365 days.

Birth and death are stochastic processes and growth varies among individuals, depending on the resources (i.e. prey) they encounter. It was therefore necessary to simulate a large number of females in order to obtain reliable estimates of mean lifetime reproductive success for a particular combination of parameter values. A minimum of 1,000 females was required to obtain consistent estimates and thus 2,000 females were chosen for the simulation.

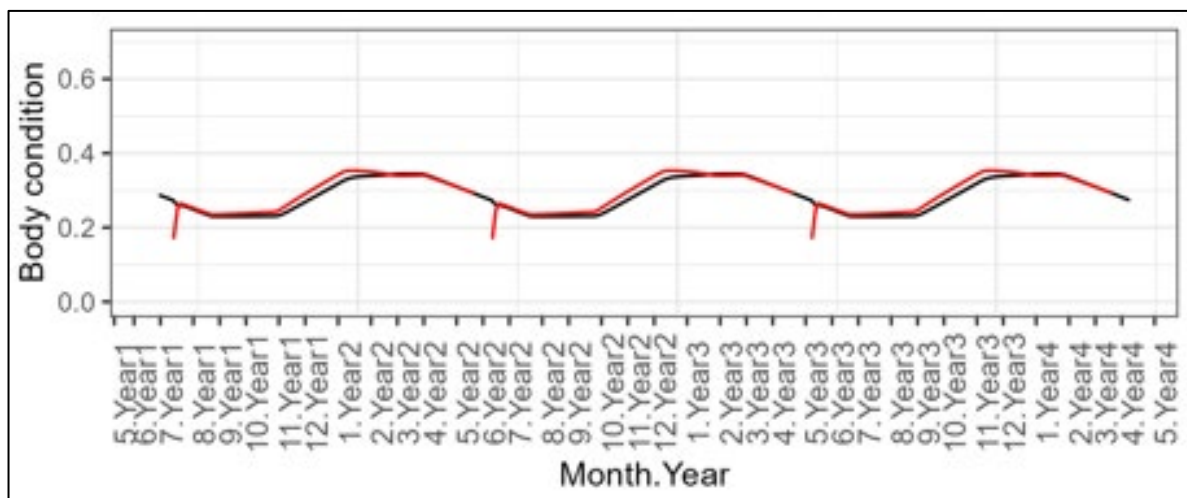


Figure 1 Predicted changes in relative body condition of an average female (black line) and her offspring (red line) over the course of 3 breeding cycles in an undisturbed environment for the period for which all calculations were done when modelling the effect of disturbance.

Modelling the environment and pattern of disturbance events

The quality of the environment is an important variable in simulations assessing the reproduction and survival of porpoises. Animals typically perform better in higher quality environments and worse when the environment is poor quality. This is challenging to define in practice but the environment in model simulations is controlled by a resource density value. For these simulations, the resource density value was calibrated to ensure the resulting outcome would be a stable population (i.e., that the environment gave rise to a proportionate number of calves to offset natural mortality). Since the SAC is a protected habitat because it has supported a relatively high density of porpoise over many



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years, this assumption is likely conservative (i.e. the quality of modelled environment may be lower than exists in reality).

Two piling schedules were provided by the Developer for the proposed pile driving. These schedules have been estimated based on the two WTG project options that the proposed development is including within the planning application (further details are provided in Section 3 of the NIS). The piling schedules are:

- **Piling schedule 1:**
 - 49 monopile WTGs and 2 monopiles for one OSP (total 51 monopiles)
 - Total 51 days piling, starting on 1st April and finishing 18th October (Figure 2)
 - Piling was scheduled to occur in each week within this period, with up to 2 piling days per week.
- **Piling schedule 2:**
 - 35 jacket WTGs and 2 monopiles for one OSP (total 140 pin piles and 2 monopiles)
 - Total 72 days piling, starting on 1st April and finishing 27th September (Figure 3)
 - Piling was scheduled to occur in each week within this period, with up to 4 piling days per week.

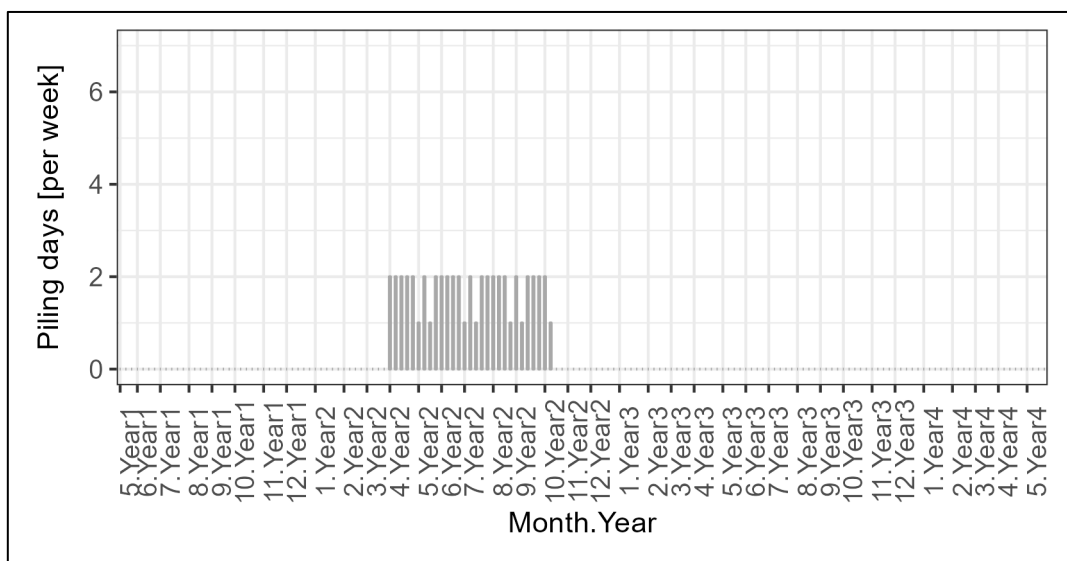


Figure 2 Piling schedule 1: 51 piling days between April and October



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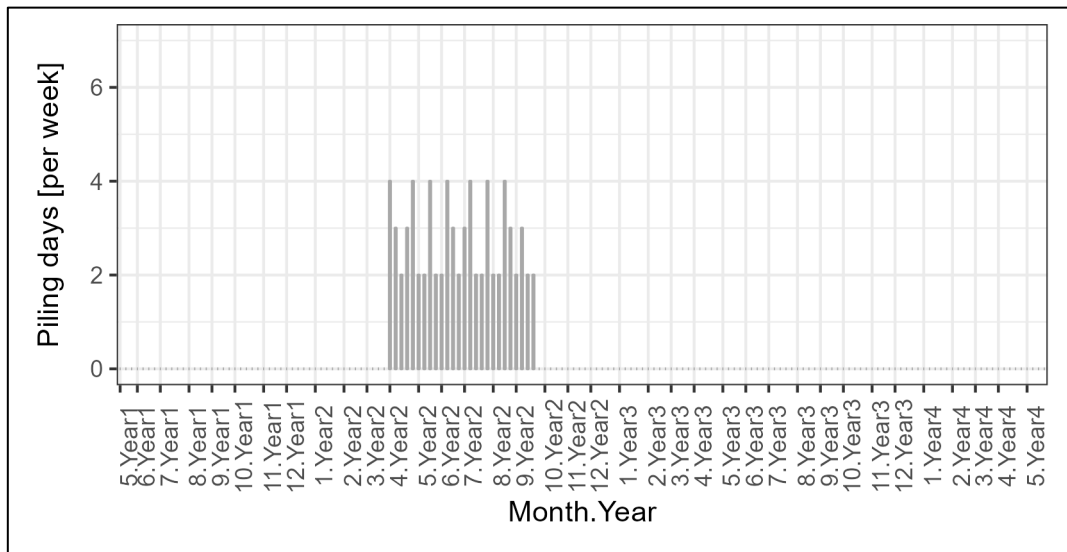


Figure 3 Piling schedule 2: 72 piling days between April and September

The effects of the piling schedule were evaluated by systematically varying the probability of disturbance and the disturbance effect. On each day of piling, it was determined whether a simulated individual would be disturbed by conducting a binomial trial using the chosen probability of disturbance. If it was disturbed, the model reduced its total assimilated energy on that day by the duration of the chosen disturbance effect expressed as a proportion of the day (e.g. a disturbance effect of 1 h resulted in a 1/24 reduction in assimilated energy). As there are no empirical data on how long individuals stop foraging after being exposed to disturbance from pile-driving noise, values of 1, 2, 4 and 6 hours per day were used for the disturbance effect. The same process was followed for each of the 2,000 simulated females. It was assumed that each disturbance event resulted in the same reduction in assimilated energy for each modelled individual (i.e. an individual would always respond in the same manner within each simulation). Overall, combinations of three **probabilities of disturbance**: 0.05, 0.1, 0.2 and four **disturbance effects**: 1, 2, 4 and 6 hours were run.

To account for parameter uncertainty, the model drew 100 combinations of values from the joint posterior distribution derived from the ABC analysis (see Appendix 1 – Details of the bioenergetic model) and used these to simulate the effect of each permutation of probability of disturbance and disturbance effect values on females that were adults when piling commenced.

For each simulation, three vital rates were documented: adult mortality rate, calf mortality rate, and birth rate (percentage of females alive at the start of the breeding season that gave birth). Birth rate and calf mortality rate were calculated for each year from the breeding season before piling commenced to the breeding season after piling ended. In order to identify significant differences between simulations with and without disturbance, Welsh’s unequal variance t-test to pairs of values that used the same combination of parameters was conducted. If a significant difference was detected, this was expressed as a percentage change from the value observed in a scenario with no disturbance. Otherwise, no value is presented – meaning there was no significant difference between the disturbed and undisturbed (no pile driving activity) scenarios.

Results

Piling schedule 1: monopiles

Figure 4 shows the predicted effects of the different combinations of values for disturbance effect and probability of disturbance resulting from piling schedule 1 (monopiles) on porpoise birth rate,



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calf mortality rate and adult mortality rate. Results are expressed as a percentage change from no disturbance.

Calf mortality rate

Across all simulations, calf mortality rate was the only affected vital rate due to the simulated pile driving activity and this only occurred in simulations with the most severe assumptions regarding probability of disturbance and disturbance effect. **In most simulations, no effect on calf mortality rate was predicted, especially where the probability of disturbance was 0.05 or where each disturbance resulted in 1-2 hours of lost foraging.**

Using the most realistic upper limits of disturbance effect (6 hour) and probability of disturbance (0.1), the result was **no significant change in calf mortality rate** from the undisturbed simulation.

Due to the uncertainty in how porpoises use the area, scenarios were explored with more extreme values (for which there is little scientific evidence to support). If these severe assumptions hold, the maximum increase in calf mortality rate was 2% under the assumptions that disturbance caused a 6h reduction in foraging and that reduction applied to 20% of the simulated individuals. This is however highly unrealistic given the evidence presented above for the likely limits of disturbance effect and probability of disturbance.

Birth rate

Pile driving resulted in **no significant change in birth rate** from the undisturbed simulation.

Adult mortality rate

Pile driving resulted in **no significant change in adult mortality rate** from the undisturbed simulation.

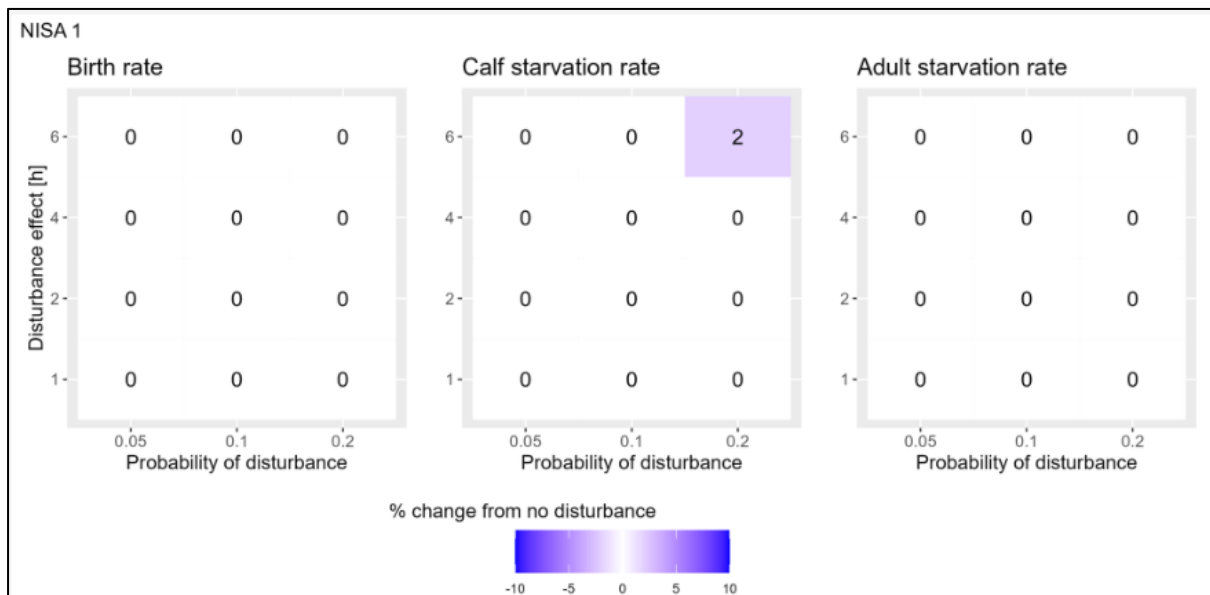


Figure 4 Piling schedule 1: Percentage change from no disturbance for three vital rates: birth rate, calf and adult mortality (from starvation) rates for combinations of probability of disturbance and disturbance effect for harbour porpoises.

Piling schedule 2: pinpiles

Figure 5 shows the predicted effects of the different combinations of values for disturbance effect and probability of disturbance resulting from piling schedule 2 (pinpiles) on porpoise birth rates, calf



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mortality rate and adult mortality rate. Results are expressed as a percentage change from no disturbance.

Calf mortality rate

Across all simulations, calf mortality rate was the main affected vital rate due to the simulated pile driving activity and this only occurred in simulations with more severe assumptions regarding probability of disturbance and disturbance effect. **In most simulations, no effect on calf mortality rate was predicted, especially where the probability of disturbance was 0.05 or where each disturbance resulted in 1-2 hours of lost foraging.**

Using the most realistic upper limits of disturbance effect (6 hour) and probability of disturbance (0.1), the result was **no significant change in calf mortality rate** from the undisturbed simulation.

Due to the uncertainty in how porpoises use the area, scenarios were explored with more extreme values (for which there is little scientific evidence to support). If these severe assumptions hold, the maximum increase in calf mortality was 2.4% under the assumptions that disturbance caused a 6 hour reduction in foraging and this reduction applied to 20% of the simulated individuals. This is however highly unrealistic given the evidence presented above for the realistic limits of disturbance effect and probability of disturbance.

Birth rate

Pile driving resulted in **no significant change in birth rate** from the undisturbed simulation.

Adult mortality rate

Pile driving resulted in **no significant change in adult mortality rate** from the undisturbed simulation.

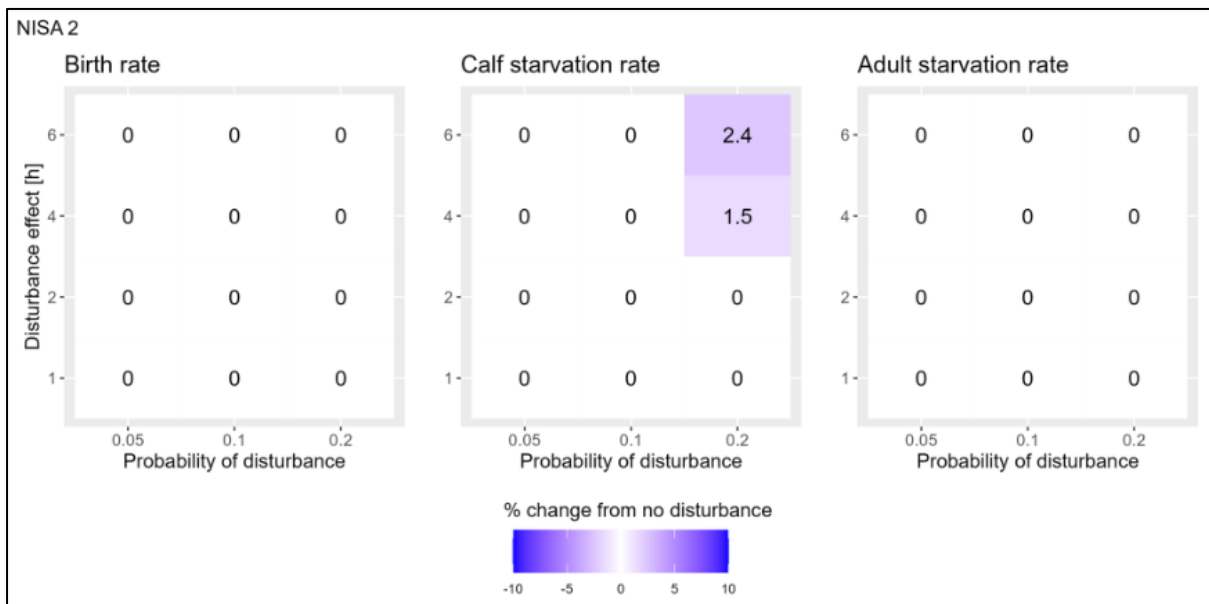


Figure 5 Piling schedule 2: Percentage change from no disturbance for three vital rates: birth rate, calf and adult mortality (from starvation) for combination of probability of disturbance and disturbance effect for harbour porpoises. The panels are shaded according to severity of the effect.



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Conservatism

It is important to note that whilst not assessed this here, it is likely that there is individual heterogeneity in the response of animals. Responses might be different between animals due to being exposed to a different received level (i.e., the probability of response increases with increasing proximity or received level from the source (e.g. summarised by Harris et al. 2018)), or due to different states of the animal (e.g. body condition, life history stage). As noted above, in the simulations it is assumed that animals respond to the same extent irrespective of their location relative to the piling location and to the same degree each time (i.e. all animals disturbed lose the same amount of energy intake). This is highly unlikely. Chudzińska et al. (2024) demonstrate that if individual heterogeneity is allowed in the probability of response – it dramatically reduces predicted impact. Further, Graham et al. (2019) highlight that the probability of response declines as the piling campaign continues.

Conclusion

It is acknowledged that a number of individuals within the Rockabill to Dalkey Island SAC, the Lambay Island SAC and the Codling Fault Zone SAC may experience disturbance as a result of pile driving at the proposed development. This disturbance effect may result in a temporary change in the distribution of individuals within these SACs, and a temporary change in behaviour whereby individual porpoise may cease foraging for a limited period of time.

Under what should be considered **the most realistic scenarios**, disturbance from pile driving at the proposed development is not expected to result in any impacts to individual harbour porpoise vital rates.

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Appendix 1 – Details of the bioenergetic model

A full description of the bioenergetic models using the ODD (Overview, Design concepts, and Details protocol), a standardised format for documenting individual-based models (Grimm et al. 2020), together with detailed information on the way in which model parameters were derived can be found in (Harwood et al. 2020, Harwood et al. 2022, Chudzińska et al. 2024).

The equations in a bioenergetics model describe the life history processes of a cohort of organisms, based on energy fluxes. Resources assimilated from the environment are allocated to maintenance, growth and reproduction via a reserve compartment.

The model presented in this report tracks the way in which individual female harbour porpoises assimilate energy over the course of their lives from weaning to death, and how this energy is allocated to daily energy needs (i.e., field metabolism), growth and the costs of reproduction (e.g., foetal development, and lactation). A simulated individual's daily assimilated energy varies with resource density, its structural mass, its state (e.g. pregnant, lactating, moulting) and its relative body condition (defined as the ratio of reserve mass to total mass). Individuals are assumed to have a target body condition (which is based on the maximum body condition observed in free-living animals (McLellan et al. 2002, Lockyer 2007)). They assimilate energy at half of the maximum possible rate when their body condition is at the target level and increase their energy assimilation progressively if their body condition is reduced below this value (see details in Harwood et al. (2020)).

If assimilated energy on a particular day exceeds the combined costs of metabolism, growth and reproduction, the surplus energy is converted to reserve tissue. If the combined costs cannot be covered by assimilated energy, the assimilated energy is assigned to growth (including growth of any foetus). If this is less than the energy required for growth, the growth rate of the female and her foetus is reduced accordingly. The daily costs of maintenance and lactation are always met in full by a combination of the assimilated energy remaining after realized growth costs have been subtracted and catabolism of reserve tissue. In these circumstances, a female's relative body condition will be reduced on the next day.

It was assumed that individuals experience an additional risk of death if their body condition falls below a starvation threshold, which is based on the minimum body condition observed in free-ranging animals. As body condition of porpoises varies seasonally (Lockyer 2007) (Figure 1), this threshold also varies seasonally between 25 and 14% (see Figure 6 in Harwood et al. 2020)

It was assumed that all adult females above a certain age can become pregnant every year. However, the actual age at first successful reproduction and the total number of offspring produced by a female depends on her body condition and life expectancy. The metabolic and growth costs of pregnancy are calculated by including foetal mass in maternal structural mass. Following New et al. (2013) and Hin et al. (2019), it was assumed that a female may choose to terminate a pregnancy at a pre-defined time, which is the day of ovulation.

Offspring are entirely dependent on milk provided by their mother until they start foraging on their own, and their demand for milk depends on their structural mass and body condition. However, following Hin et al. (2019), it was assumed that adult females would reduce the amount of milk they actually provide to their calf as their own body condition declines. Independent foraging is assumed to begin during lactation. Calf foraging efficiency is assumed to increase with age until it attains the adult value.



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Quantifying uncertainty around model parameter values in the bioenergetic model

The bioenergetics models require values for more than 50 parameters (see full list in Chudzińska et al. (2024)), some of which are not directly observable, and it is important to try to quantify the uncertainties that are associated with the values used for these parameters. Rejection Approximate Bayesian Computation (ABC) (Lagarrigues et al. 2015) was used to establish plausible statistical distributions for the unobservable parameters, and for other parameters whose reported values showed large variations

The ABC approach involves: (i) defining a set of rejection criteria based on empirical information that can be used to evaluate the plausibility of outputs from a model with a particular set of parameter values; (ii) simulating the model a large number of times with values drawn from prior distributions for the parameters under investigation; (iii) comparing the simulation outputs to the rejection criteria; and (iv) retaining only those combinations of parameter values that produce outputs that fall within the plausible range. This process generates a joint posterior distribution for the parameters under investigation.

The parameters chosen for ABC were: effect of age on foraging efficiency, age of offspring when foraging efficiency was 50% of the adult level, starvation threshold and starvation mortality, field metabolic rate scalar, resource density and calf age at which female begins to reduce milk.

300,000 simulations were run for 2,000 females each, in the absence of disturbance, with parameters drawn from a prior distribution (Chudzińska et al. 2024).

The rejection criteria was developed based on the following population characteristics: population growth rate; proportion of females giving birth each year; female starvation mortality; and offspring survival rate (Chudzińska et al. 2024).

The joint posterior distribution of parameter value combinations that fulfilled the rejection criteria for each species are shown in Chudzińska et al. (2024). This distribution was then sampled at random to provide parameter values for the simulations.