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Maritime traffic alters distribution of the harbour porpoise in the North Sea

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A R T I C L E I N F O

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A B S T R A C T

The North Sea is one of the most industrialised marine regions globally. We integrated cetacean-dedicated aerial surveys (2015–2022) with environmental covariates and ship positions from the Automatic Identification System (AIS) to investigate the disturbance radius and duration on harbour porpoise distribution. This study is based on 81,511 km of line-transect survey effort, during which 6511 harbour porpoise groups (8597 individuals) were sighted. Several proxies for ship disturbance were compared, identifying those best explaining the observed distribution. Better model performance was achieved by integrating maritime traffic, with frequent traffic representing the most significant disturbance to harbour porpoise distribution. Porpoises avoided areas frequented by numerous vessels up to distances of 9 km. The number of ships and average approach distance over time improved model performance, while reasons for the lower performance of predicted ship sound levels remain unclear. This study demonstrates the short-term effects of maritime traffic on harbour porpoise distribution.

1. Introduction

Anthropogenic activities are profoundly altering the ocean soundscape (Hildebrand, 2009; Miksis-Olds and Nichols, 2016; Popper et al., 2020), with maritime traffic being recognized as the most pervasive source of marine continuous noise pollution globally (Frisk, 2012; Malakoff, 2010; Tournadre, 2014). The North Sea is one of the busiest shipping traffic areas in the world and maritime traffic continues to increase (Kaplan and Solomon, 2016), among others due to activities related to the construction of infrastructures in the framework of energy supply and transport (offshore windfarms, energy islands, oil and gas extraction, the laying of cables and pipelines), while underwater radiated ship noise is recognized as a significant conservation concern (Dekeling et al., 2014; International Maritime Organization [IMO], 2014).

Strong evidence exists on direct impacts of maritime traffic on marine mammal behaviour and physiology (Duarte et al., 2021). The harbour porpoise (*Phocoena phocoena*), the most abundant cetacean species in the North Sea (Gilles et al., 2023), is particularly vulnerable to anthropogenic disturbances (Wisniewska et al., 2016) as it must forage almost continually. The species is strictly protected in the EU (e.g. Habitats Directive; (Sands and Galizzi, n.d.)). Previous studies, using visual observations or bio-logging data (Barlow et al., 1988; Frankish et al., 2023; Goodwin, 2007; Palka, 2002; Wisniewska et al., 2018), have demonstrated that individuals avoid ships and change their behaviour at several kilometres away from ships. Passages of loud ships coincide with vigorous fluking, porpoising, diving to the bottom, and the cessation of foraging, resting and echolocation (Wisniewska et al., 2018; Dyndo et al., 2015). Studies also found that harbour porpoise density is significantly lower in areas of high maritime traffic than in adjacent areas without intense shipping (Akkaya Bas et al., 2017; Nehls et al., 2023; Oakley et al., 2017; Roberts et al., 2019; Terhune, 2015). Furthermore, observations have shown that disturbed porpoises only reappear 8 to 20 min after a ship has passed or has left the area completely (Goodwin, 2007; Oakley et al., 2017; Roberts et al., 2019). Lastly, it has been shown that porpoises are frequently deterred by ships,

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both during day and night, in a busy area such as the western Baltic Sea (Frankish et al., 2023).

In summary, harbour porpoises are clearly sensitive to the presence and noise of maritime traffic and the likelihood of these animals being displaced from important foraging grounds on a population scale is thus critical (Gallagher et al., 2021). However, the sound levels that the animals are exposed to are difficult to measure or model (Erbe et al., 2019), and the type and magnitude of the responses might depend on both external factors, e.g. ship characteristics and speed, background noise level, habitat quality (Goodwin, 2007), and individual-specific factors, e.g. specific hearing abilities, behavioural context, previous experience (Cox et al., 2001; Ellison et al., 2012; Southall et al., 2021).

To extend the results obtained from observational and tagging data in our investigation of the large-scale impacts of maritime traffic on harbour porpoise distribution in the North Sea, we use species distribution models (SDMs) and Automatic Identification System (AIS) data. We test several proxy variables to investigate those that would best capture the disturbance caused by maritime traffic. We assume that 1) harbour porpoise occurrence decreases in areas of high maritime traffic, and that underwater radiated noise from ships is the main cause, 2) the model explaining harbour porpoise distribution will improve with the proxy variable that best reflects the disturbance of ships. In addition, 3) optimising the temporal and spatial dimension used for the proxy variable will increase model performance.

2. Material and methods

The entire workflow is illustrated in a flow chart (Fig. 2), including the processing of survey data, environmental covariates, vessel information, as well as an overview of the data analysis. More details are provided in the following sections. All analyses were performed with RStudio (R version 4.2.1, (R Core Team, 2022)).

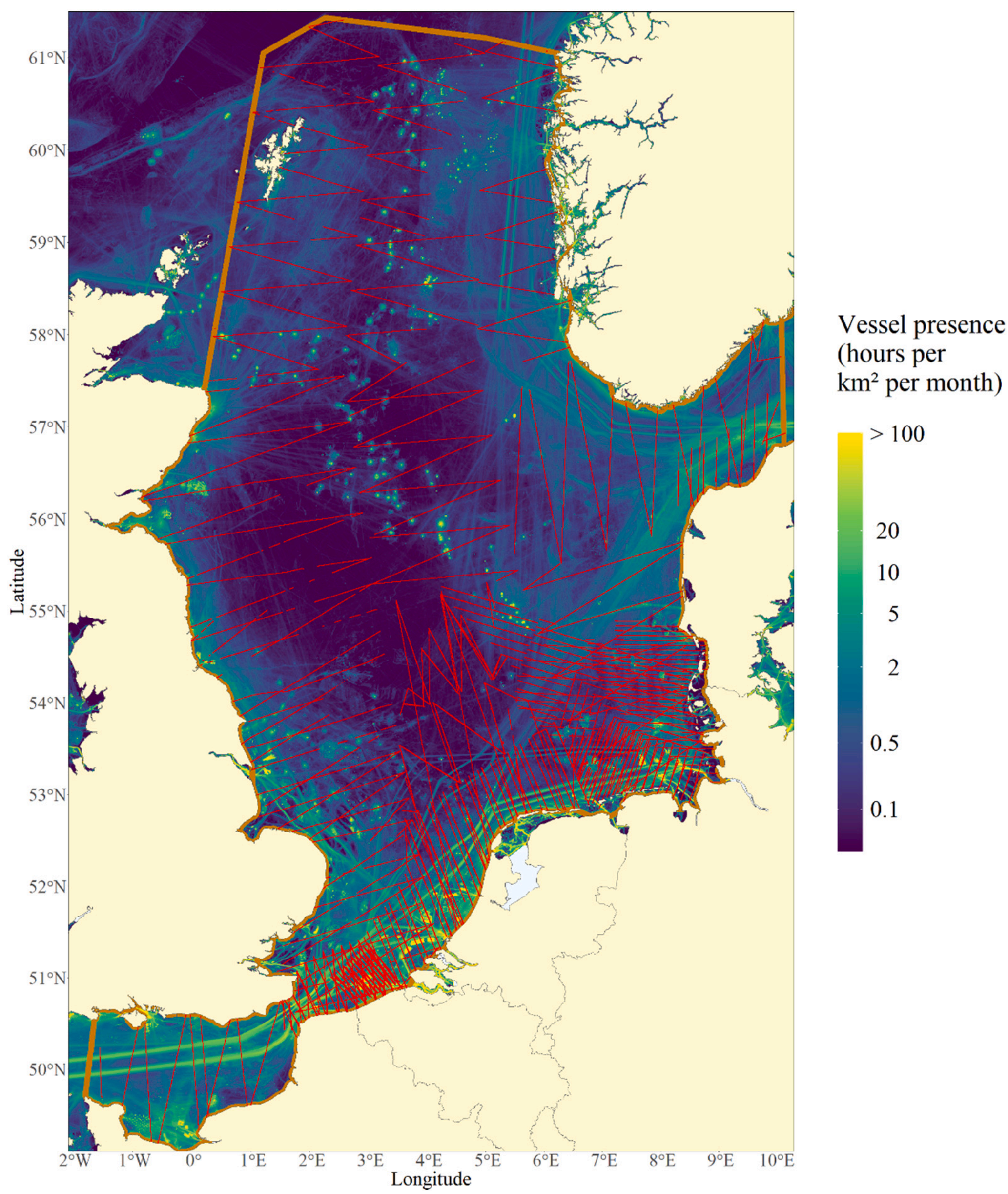

Fig. 1. Cetacean surveys conducted in the North Sea between March 2015 and March 2022 (red lines) and average vessel density in 2022 (source: EMODnet (EMODnet Digital Bathymetry (DTM), 2022)). Orange lines bound the study area, which covers regions of low and high vessel density (e.g. Dogger Bank, in the central North Sea, versus the English Channel, in the southern North Sea, where ships can be up to 500 h/km^2/month). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.1. Harbour porpoise sightings

Dedicated cetacean visual surveys conducted in the frame of national monitoring programmes by Germany, the Netherlands, Belgium, Denmark and France in the North Sea as well as data from the large-scale SCANS-III survey in 2016 (Small Cetaceans in the European Atlantic and North Sea; (Hammond et al., 2021) were aggregated across the study area (Fig. 1; covering 601,447 km^2). The data were filtered for the period from March 2015 to March 2022, corresponding to the period when AIS data were available at good quality over the entire study area. All surveys followed the line-transect distance-sampling methodology, i.e. allowing to estimate the detection probability from the transect line and to estimate absolute abundances, by also accounting for the fraction missed on the transect (Buckland et al., 2004; Hammond et al., 2013). Detailed descriptions of aerial survey field data collection methods are provided in previous studies (Hammond et al., 2021; Gilles et al., 2009; Gilles et al., 2016; Scheidat et al., 2008). The survey data were delimited to the North Sea (Fig. 1) and the individual transects were segmented into 10 km length segments, conform (Gilles et al., 2016; Becker et al., 2020; Virgili et al., 2019). This resulted in 7593 segments that covered 81,511 km in 123 days, with 6511 harbour porpoise sightings (8597 individuals). Of these, 81.5 % of the data were collected during the meteorological summer (June–August), 2.7 % during the autumn (September–November), 1.2 % during the winter (December–February) and 14.6 % during the spring (March–May).

2.2. AIS data

AIS data were aggregated to build the most comprehensive AIS data set possible from three different sources: the European Maritime Safety Agency (EMSA), the Danish Maritime Authority (www.dma.dk) and the German Federal Agency for Nature Conservation (BfN). The tracks of the vessels were merged by unique Maritime Mobile Service Identity (MMSI) and duplicate points were removed (Schwarzkopf et al., 2021).

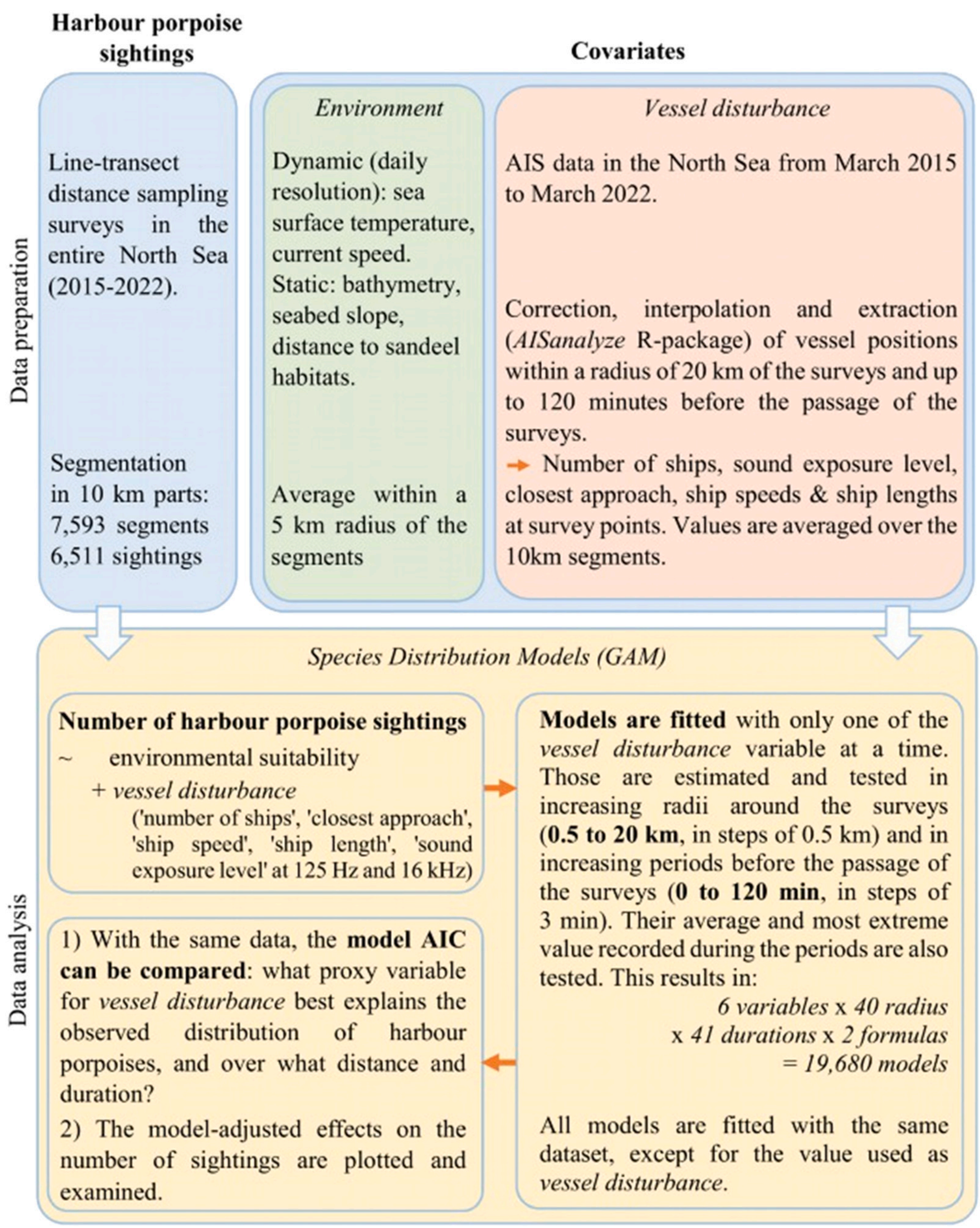

Fig. 2. Flow chart of data preparation steps and analyses. *AISanalyze* R-package is available at github.com/AISanalyze and sustainMare/products.

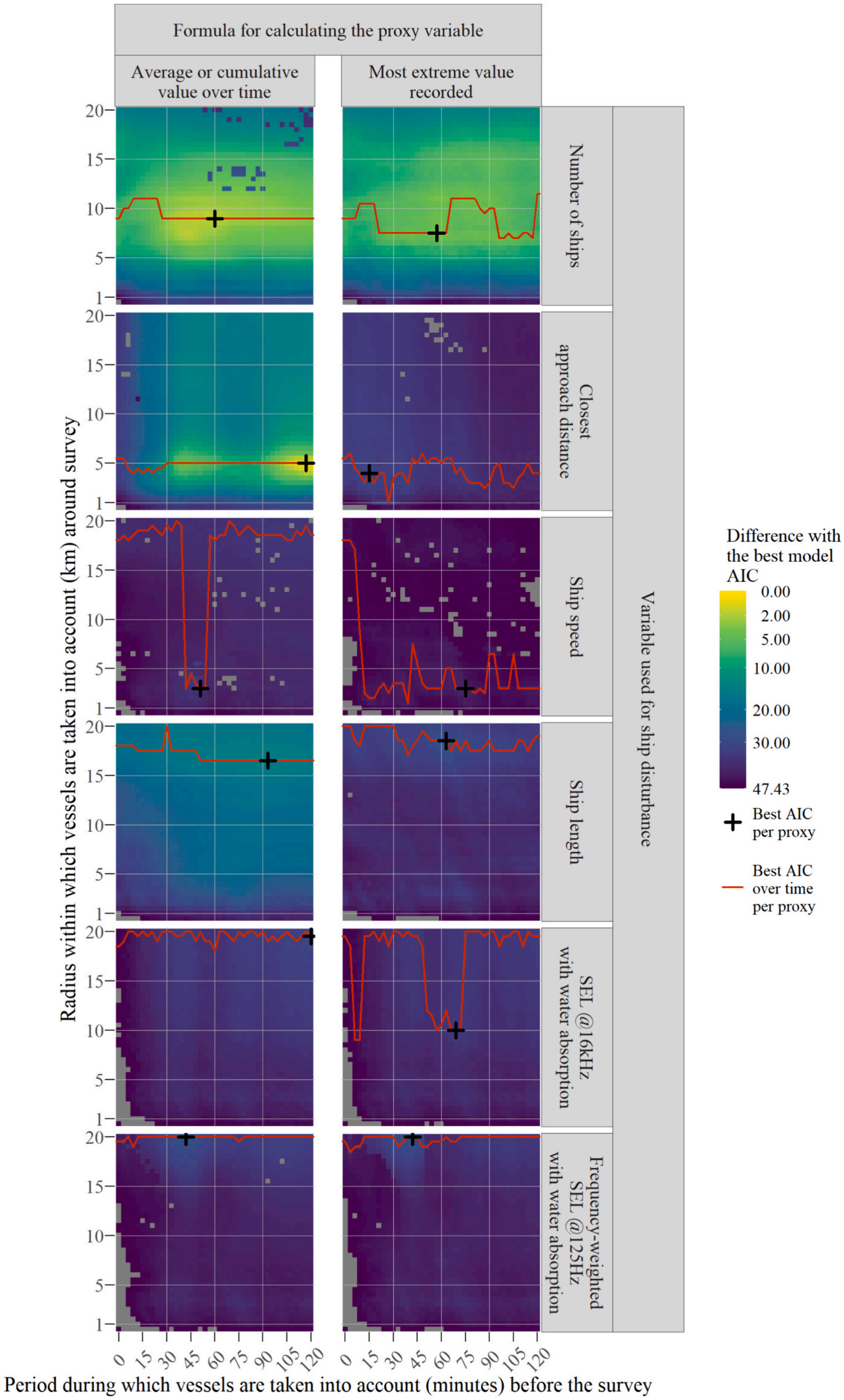

Fig. 3. Model AIC per proxy variable, according to the radius and period considered before the survey. Proxy calculations are detailed in Table 1. The ΔAIC is calculated compared to the best overall model. The threshold 47.43 is the ΔAIC of the model without proxy variable (environmental variables only, see Table 3): models with higher ΔAIC can be considered as unsuitable and are displayed in grey.

We created the *AISanalyze* R-package (available at github.com/AISanalyze) to correct Global Positioning System (GPS) errors, interpolate vessel positions in 4 s intervals – equivalent to the GPS temporal resolution of the aerial survey data. Vessel positions were extracted up to 20 km from the survey transects and up to 120 min before the passage of the surveys as it has been demonstrated that vessels can be heard over long distances and durations at low ambient noise levels (Findlay et al., 2023). Errors in vessel lengths and vessel types in the AIS data were corrected with *AISanalyze*, filtering out unrealistic values (i.e. lengths of 0 or >459 m, the longest ship currently in operation worldwide) and using the most frequent values occurring over the years per ship. The vessels were categorised as fishing, tug, naval, recreational,

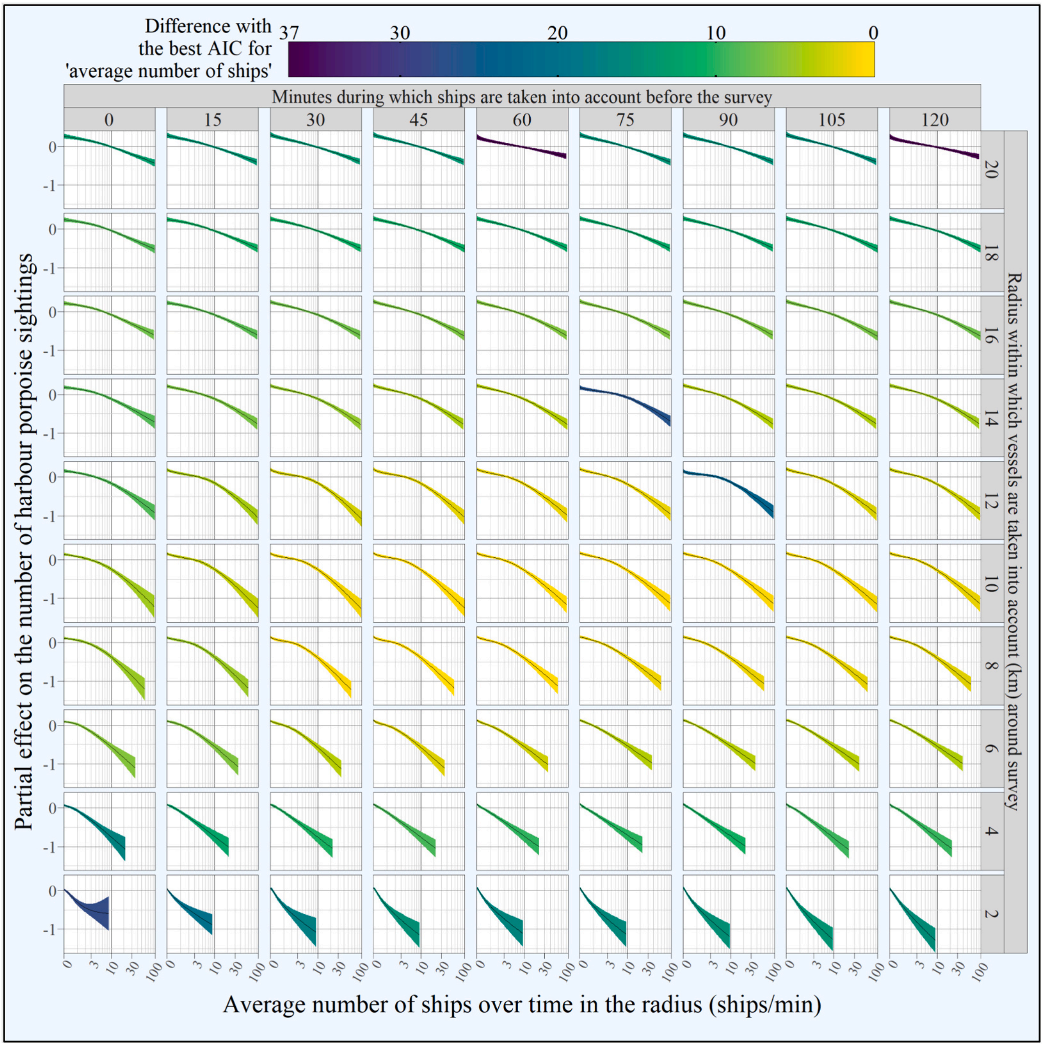

Fig. 4. Model-adjusted effects of the 'average number of ships' over time on the number of harbour porpoise sightings, according to the radius and period considered before the survey. The partial effect of a covariate is its isolated influence on the response variable, after accounting for the effects of all other covariates in the model. In a 9 km radius, the average presence of 5 to 7 ships/min decreased the expected number of porpoise sightings by a quarter, while 14 to 21 ships/min decreased it by half.

government/research, cruise, passenger vessels, bulker, containership, vehicle carrier, tanker, dredger or other (MacGillivray and de Jong, 2021). The regulation requires that AIS is installed aboard all ships exceeding 300 gross-tonnage involved in international voyages, 500 gross tonnage for other voyages, and aboard all passenger ships regardless of size (except warships). Although AIS data does not include most small recreational boats, larger vessels probably contribute more to the marine soundscape due to their number, size and speed (Findlay et al., 2023), especially in offshore areas, and hence might be most relevant in terms of influencing harbour porpoise distribution.

2.3. Calculation of the proxy variables for vessel disturbance

Six variables were each tested using two different calculation formulas ('average value' and 'most extreme value' predicted over time, see Table 1), resulting in 12 proxy variables tested. These were extracted within different radii around the segments (from 0.5 to 20 km, in steps of 0.5 km) and over different periods preceding the plane's passage (from 0 to 120 min, in steps of 3 min) to investigate their radius and duration of impact. This resulted in 1640 unique combinations of tested radius and period for each of the 12 proxy variables. The calculations were computed on the supercomputers as part of the NHR infrastructure (see acknowledgments).

The ship sound source levels (SL) were modelled in the 125 Hz and 16 kHz decidecade frequency band with the JOMOPANS-ECHO model (MacGillivray and de Jong, 2021) as a function of ship length, speed, and type. It has been shown that harbour porpoises interrupt foraging at received sound levels above 96 dB re 1 μPa in the 16 kHz decidecade band (Wisniewska et al., 2018). On the other hand, given the typical spectra of vessel sound which decrease with increasing frequency, high vessel sound levels at high frequencies are very likely to result in high sound levels at low frequencies (Hermannsen et al., 2014). The 125 Hz decidecade band is an indicator for the EU's Marine Strategy Framework Directive (MSFD) to monitor shipping noise (Tasker et al., 2010; Dekeling et al., 2013), and sound absorption by water is negligible in this frequency band, allowing sound to propagate over long distances. The received sound levels were frequency-weighted in this frequency band, conform to Southall et al. (2019), to account for the harbour porpoise hearing sensitivity.

The absorption loss α (dB/km) of sound in water was calculated according to Ainslie and McColm (1998), as a function of the frequency, temperature, bathymetry and salinity. The propagation loss between the ships and the surveyed points was estimated with a factor of 15 as a practical approximation for complex environments and mid-point

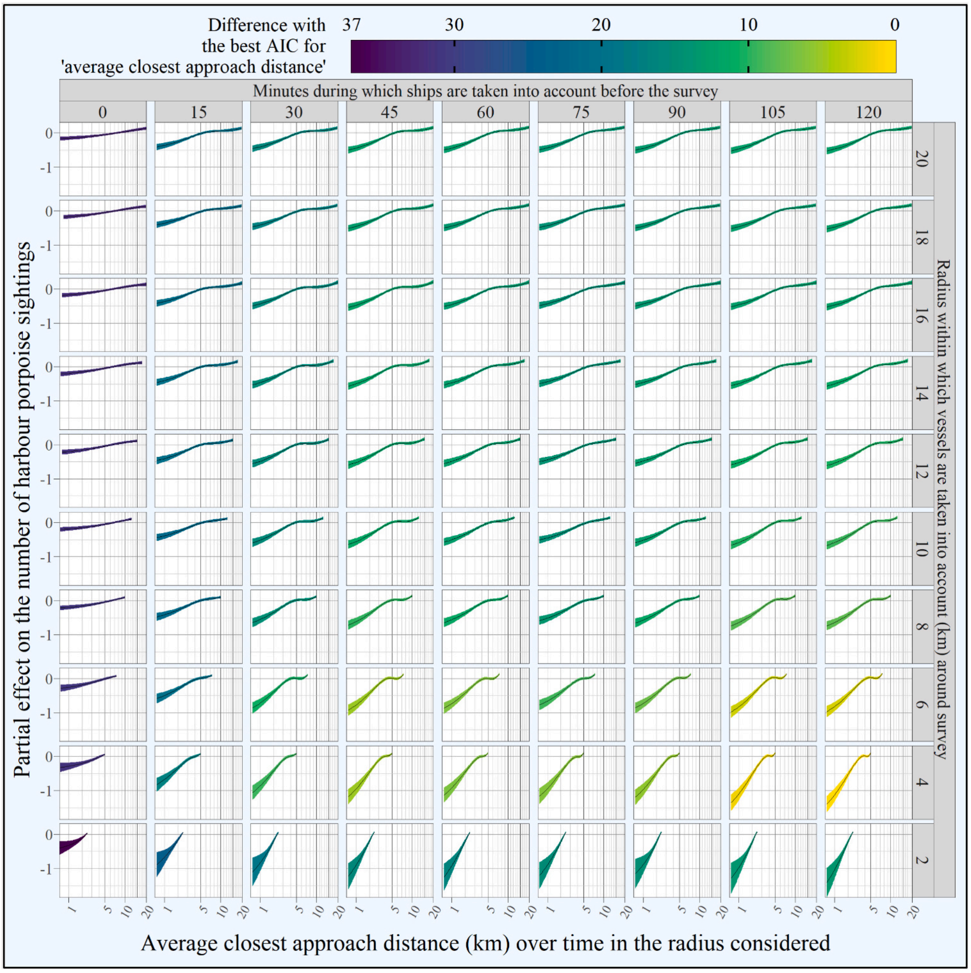

Fig. 5. Model-adjusted effects of the 'average closest approach distance' over time on the number of harbour porpoise sightings, according to the radius and period considered before the survey. Areas approached by vessels, during >15 min, closer than 2.3 to 3.1 km on average had a quarter-fewer sightings than the expected number of porpoise sightings. Areas approached closer than 1.2 to 2.1 km for >30 min had half the expected number sightings.

between shallow waters and deep waters (Erbe et al., 2022). Thus, the predicted received sound levels RL_i from a ship i at a distance of d_i metres were:

$$RL_i = SL_i - 15\,log_{10}(d_i) - \alpha * d_i$$

The received sound levels were predicted, for each survey GPS point, in 3-minute intervals from the time of the survey until 120 min before, and assuming an ambient noise A of 90 dB at 125 Hz and 70 dB at 16 kHz (Schaffeld et al., 2020). These values are consistent with survey conditions, carried out under good weather conditions, i.e. without rain or strong winds, which are among the main natural sources of noise in the marine environment (Hildebrand, 2009; Wille and Geyer, 1984). The received sound levels were:

$$RL_t = 20\,log_{10}\left(10^{\frac{A}{20}} + \sum_i 10^{\frac{RL_i}{20}}\right)$$

The predicted sound exposure levels (SEL) received at surveyed points from t_{max} minutes before the survey to the time of the survey were computed as:

$$SEL = 10\,log_{10}\left(\sum_{t=0}^{t_{max}} 3*60*10^{\frac{RL_t}{10}}\right)$$

where $10^{\frac{RL_t}{10}}$ was the sound pressure at the survey point from [t to t + 3] minutes.

2.4. Environmental covariates

Environmental covariates (Table 2) were used to estimate the effects of maritime traffic on the number of porpoises, taking into account environmental suitability. They were selected following previous studies on the distribution of harbour porpoises (Gilles et al., 2016; Geelhoed et al., 2022; Lacey et al., 2022). The season could not be considered as grouping factor due to the lack of data in winter, spring and fall, so sea surface temperature and day length were both tested as proxy variables for the season (Gilles et al., 2016). The species-environment relationships were found to be more ecologically rational with sea surface temperature than with day length, and they remained stable when proxies for maritime traffic were incorporated into the models. On this basis, we selected the environmental covariates (Table 2) used to analyse the effect of maritime traffic. These are proxies for habitat suitability and prey availability, probably the main drivers of small cetacean distribution (Palacios et al., 2006; Redfern et al., 2006). The daily covariate averages were extracted within a 5 km radius around the segments.

2.5. Model fitting

The values of the environmental covariates and the 19,680 estimates of vessel disturbance proxy variables per radius and per period were joined to the 7593 segments of survey data. Generalised Additive Models (GAMs (Wood, 2017)) were fitted to this dataset: the number of harbour porpoise sightings was defined as the response variable, the

Table 1
Proxy variables for vessel disturbance as tested in the distribution models for harbour porpoises.

Variable for vessel disturbance	Proxy calculations used over the period preceding the survey and within the area	Justification
Number of ships	- Average number of ships over time. - The highest number of ships recorded during the period.	A high number of ships over a long or short period could deter harbour porpoises.
Closest approach distance (km)	- Average over the period of the closest vessel approach distance to the survey point. - Minimum approach distance of ships to the survey point recorded during the period (classified as 'most extreme value recorded' in Fig. 3).	Areas frequently used by ships can discourage porpoises from approaching. This gives an index of distance from maritime traffic. However, a single, close approach of a vessel could also deter harbour porpoises.
Vessel speeds (km/h)	- Sum of vessel speeds in the radius, averaged over time. - The highest vessel speed recorded during the period.	The sum is used to cumulate ship disturbances in the radius, taking into account either their speed or their length as the main parameter influencing the noise emitted. These sums are tested as simple, easy-to-calculate indicators of ship noise. Averaging them over time gives an index of disturbance over the period. On the other hand, a fast vessel or a large vessel over a short period could deter harbour porpoises due to the noise produced.
Vessel lengths (m)	- Sum of vessel lengths in the radius, averaged over time. - The longest vessel recorded during the period.	
Sound exposure level (SEL) at 16 kHz, accounting for water absorption	- Cumulated sound exposure level over time (dB re 1 μPa^2 s). - The highest received sound exposure level (dB re 1 μPa^2) predicted during the period.	- Noisy areas over a long or short period could be avoided by harbour porpoises.
Sound exposure level (SEL) at 125 Hz, frequency-weighted for harbour porpoise hearing sensitivity and accounting for water absorption	- Cumulated sound exposure level over time (dB re 1 μPa^2 s). The highest received sound exposure level (dB re 1 μPa^2) predicted during the period.	

environmental variables plus one of the vessel disturbance proxy variables were defined as explanatory variables. The natural logarithm of the effective area searched (in square kilometres) was defined as an offset to account for the varying segment lengths and detection probabilities related to sighting conditions (Buckland et al., 2004; Gilles et al., 2016). Another GAM was fitted only with environmental variables, as a reference to distinguish unrealistic models. A negative binomial distribution was used to account for overdispersion and the splines were fitted with cubic regression splines with 4 knots to limit overfitting (Virgili et al., 2018). This resulted in 19,681 comparable models. The models were fitted with the restricted maximum likelihood (REML) method using the *mgcv* R-package (Wood, 2011).

2.6. Data analysis

The AIC (Akaike, 1998) of the 19,681 models were extracted, as well as the Chi-Square and *P*-values of the proxy variable used for ship disturbance. Only AIC results are presented in the following as a criterion of model quality, but similar and consistent results were found between these three metrics.

The model-adjusted effects of the proxy variables were extracted for different radii (from 2 to 20 km, in 2 km steps) and periods (from 0 to 120 min before the survey, in 15 min steps). The proxy variables with the lowest AIC (e.g. 'average number of ships' and 'average closest approach distance' over time) were plotted in the Results section. The Spearman's correlation coefficient was calculated between their values at respective optimal radius and duration to determine whether they could be included in a single model. Model-adjusted effects for other proxies are provided in the Supplementary figures. These plots allow checking the plausibility of the model-adjusted effects and of the proxy variables.

3. Results

3.1. Model performance

The optimal radii and periods were different between the proxy variables (Fig. 3, Table 3), but relatively similar between the 'average (or cumulative) value over time' and the 'most extreme value recorded' for each variable individually (e.g., number of ships, or received sound level). The closest approach distance was an exception: the best models of the 'average closest approach distance' were obtained for longer periods (around 120 min) than the best models of the 'minimum approach distance' (around 15 min). For every proxy, the best performances of the 'average (or cumulative) value over time' exceeded those of the 'most extreme value recorded'.

Overall, the best performances (i.e. ΔAIC < 2 compared to the best model, see Table 3) were reached by the 'average closest approach distance' within 4 to 5.5 km over 105 to 120 min, and by the 'average number of ships' within 7.5 to 9.5 km over 36 to 66 min. The calculation of the Spearman's correlation between these two proxy variables at optimal radius and period was -0.89: areas regularly approached by ships over 105 to 120 min were often areas with a high number of ships in a 7.5 to 9.5 km radius.

The model AIC for the 'average number of ships' and 'highest number of ships' gradually and consistently decreased to the minimum, which best explains the observed occurrences of porpoises, and increased again with larger distances and longer durations. For the 'average closest approach distance', a first minimum of AIC was detected for a 5 km radius over 40 min. Then, the AIC consistently decreased to the optimal radius and duration (see results in Table 3).

The 'highest number of ships' showed good performances as well (the lowest AIC being found for 57 min within 7.5 km, Fig. 3). The model performance declined with the 'sum of vessel lengths averaged over time' but the *P*-value remained below 2×10^{-16}. The other proxy variables, including those associated with the prediction of vessel sound levels gave lower performance, especially the 'highest vessel speed'. The *P*-values were significant for all proxy with optimised parameters (Table 3).

3.2. Effect of vessels on distance and time

The number of sightings of harbour porpoises decreased with a higher 'average number of ships' within the radius over time, and with a shorter 'average closest approach distance' over time (Figs. 4 and 5). This was the case for all the radii and periods considered (from 0.5 to 20 km, and from 0 to 120 min before the survey), but the magnitude of the effects consistently increased up to the optimal radii and periods. Especially, the drop in the number of sightings was more pronounced in

Table 2
Environmental variables used, in addition to the proxy variable for vessel disturbance.

Environmental covariate	Original spatial resolution	Original temporal resolution	Source	Justification
Bathymetry (m)	1/16 arc minute	NA	EMODnet (EMODnet Digital Bathymetry (DTM), 2022)	Proxy for cetacean prey distribution
Slope (rad)	1/16 arc minute	NA	Derived from bathymetry (*terrain* function from *terra* R-package (Hijmans, 2024))	Associated with currents, high slopes induce enhanced primary production or prey aggregation.
Distance to sandeel (*Ammodytes* spp.) fishing grounds (m)	NA	NA	Jensen et al. (2011), applied in (Gilles et al., 2016)	Sandeels are important prey species for harbour porpoises (Pierce and Santos, 2003) and for piscivorous fish, which are also preyed on by porpoises. Sandeels were shown to be among the 'big four' of the harbour porpoise diet in the southern North Sea, besides gobies, gadoids, and clupeids (Leopold and Meesters, 2015).
Mean sea surface temperature (°C)	0.083° (−5500 m to 0 m)	Daily	Copernicus (Atlantic-European North-West Shelf models (NWSHELF_MULTIYEAR_PHY_004_009, n.d.))	Variability over time and horizontal gradients of SST reveal front locations and mixing of waters. They are associated with enhanced primary production and prey aggregations.
Current speed (m/s)	0.083° (−5500 m to 0 m)	Daily	Copernicus (Atlantic-European North-West Shelf models (NWSHELF_MULTIYEAR_PHY_004_009, n.d.))	Intensity of tidal current

Table 3
Summary of the best model per vessel disturbance proxy variable, ranked by increasing AIC. The ΔAIC is calculated compared to the best overall model (rank 1 below). Models with a ΔAIC < 2 are shown in bold.

ΔAIC	Proxy variable	Rank among the 19,681 models	P-value	Chi-Square	Radius (km)	Minutes preceding the survey
0.00	**Average closest approach distance**	**1**	**$<2\times10^{-16}$**	**50.08**	**5**	**117**
1.45	**Average number of ships**	**11**	**$<2\times10^{-16}$**	**50.17**	**9**	**60**
2.51	Highest number of ships	107	$<2\times10^{-16}$	48.45	7.5	57
14.53	Sum of vessel lengths averaged over time	3121	$<2\times10^{-16}$	36.07	16.5	93
27.44	Longest vessel	5824	1×10^{-5}	21.80	18.5	63
28.31	Cumulated sound energy over time (125 Hz)	5895	5×10^{-5}	20.72	20	42
28.63	Highest received sound level (125 Hz)	5923	6×10^{-5}	20.60	20	42
30.64	Minimum approach distance	6155	2×10^{-5}	17.31	4	15
31.24	Cumulated sound energy over time (16 kHz)	6245	5×10^{-5}	17.28	19.5	120
33.20	Sum of vessel speeds averaged over time	6872	2.9×10^{-4}	16.64	3	51
33.84	Highest received sound level (16 kHz)	7221	3×10^{-4}	14.86	10	69
39.40	Highest vessel speed	12,622	2.6×10^{-3}	8.58	3	75
47.43	None (environmental variables only)	19,234	NA	NA	NA	NA

areas frequently approached by ships at distances of <5 km or 7 km over time. At greater 'average closest approach distances', the effect on the number of sightings reached a plateau. For all the other proxy variables tested, lower levels of ship disturbance were also correlated with higher numbers of harbour porpoise sightings.

4. Discussion

We conducted the first population-wide impact study on harbour porpoise distribution. The results showed that integrating proxies for maritime traffic improved the performance of harbour porpoise distribution models in the North Sea. Porpoises avoided areas with heavy or frequent maritime traffic, i.e. where the average number of ships is high within a radius of 9 km or ships frequently pass nearby. Overall, the cumulated disturbances over time gave better results than the highest disturbance encountered before the survey, probably because chronic disturbances are more prevalent than occasional ones. However, the prediction of vessel sound levels did not present the strongest correlation with the observed number of harbour porpoises.

4.1. Accurately predicting the received sound levels and the disturbance caused over large areas is challenging

We expected vessel sound levels to be one of the most important proxy variables, and to show stronger effects than the number of ships because of its more direct relationship with the disturbance (Frankish et al., 2023; Wisniewska et al., 2018; Dyndo et al., 2015). It emerged that the number of vessels and average proximity to maritime traffic, however, were more strongly correlated with the number of porpoises. This could be due to the uncertainties in predicting received sound levels, for example related to differences in vessel engines, noise spectra (MacGillivray and de Jong, 2021) and propagation loss. Echo sounders, fish finders and boat sonars are other source of noise that are not included in our study but send out pulse signals in a narrow beam towards the bottom (Hildebrand, 2004) at high frequencies audible for porpoises (Kastelein et al., 2002; Ruser et al., 2016). The increasing use of dynamic positioning on board ships, e.g. from construction vessels for offshore windfarms, can also increase the actual noise levels (Kyhn et al., 2014; Merchant et al., 2016; Penã, 2019; Rutenko and Ushchipovskii, 2015). Furthermore, uncertainties and gaps in the AIS data (Nachtsheim et al., 2023) may also lead to substantial errors in the predicted received levels and another reason for the poor predictive power of the predicted vessel sound: small, noisy recreational crafts and vessels that have switched off their AIS transmitters could create local noise disturbances, for example, that are not highlighted here. The effect of turbidity on sound absorption and the reflection at the surface or on various seabeds are additional sources of uncertainty to predict the received sound levels, which were not integrated due to the complexity of the environments over the North Sea.

Further reducing the uncertainties over large areas such as the North Sea is resource-intensive. Moreover, harbour porpoises may exhibit complex responses to vessel noise (Frankish et al., 2023; Wisniewska et al., 2018; Dyndo et al., 2015), which may be influenced by factors beyond the sound levels themselves. Differences between the hearing thresholds and tolerances of individual harbour porpoises (Dyndo et al., 2015; Kastelein et al., 2017) or high local density of prey could contribute to variability that constraints the model's capacity to capture the actual disturbance of predicted vessel sound levels. These individual-specific factors could not be integrated into our analysis, as the objective of aerial surveys was foremost to collect reliable information on the regional distribution and abundance of cetaceans.

4.2. The number of surrounding vessels and proximity to maritime traffic could give valuable information on the actual vessel disturbance

A visualisation of the survey transects, porpoise observations and real-time AIS positions during the surveys (see Supplementary video 1) showed that harbour porpoises largely avoided areas with high numbers of ships. In some cases, this was found in areas with stationary vessels, such as anchorage areas. The commonplace anchoring of high-tonnage ships has been found to cause impacts on the seabed that can last for >4 years (Watson et al., 2022). Watson et al. (2022) showed that the anchor of a high-tonnage ship (>9000 gross tonnage) can excavate the seabed by up to 80 cm and displace up to 2800 m^3 of sediments, which can affect the carbon cycle and the local marine ecosystem (Davis et al., 2016; Broad et al., 2020), potentially leading to lower prey availability.

Previous studies have reported lower occurrence of harbour porpoises with higher number of vessels (Akkaya Bas et al., 2017; Roberts et al., 2019; Haelters et al., 2023). Roberts et al. (2019) observed, within a radius of 6 to 10 km in the waters off Berry Head (South-West England), a decrease in the number of porpoises consistent with our values.

On the other hand, frequent vessel approaches could produce repeated high received sound levels in the area (Dyndo et al., 2015; Findlay et al., 2023; Hermannsen et al., 2014) and explain the stronger correlation of average closest approach distances over time than the predicted sound levels in our analysis. The first considers only the closest ship and could show that vessels have a strong effect up to around 5 km, as reported in previous studies (Frankish et al., 2023; Wisniewska et al., 2018), but this effect is not adequately captured by the received sound levels predicted in our study.

Interestingly, the effect magnitude of the average approach distance over time was much more important than the closest approach distance, for which the disturbance seems to last over a short period (around 15 min, Fig. A.2). This corresponds to the results of previous studies, showing that ships disturb porpoises from several kilometres away (Barlow et al., 1988; Frankish et al., 2023; Goodwin, 2007; Palka, 2002; Wisniewska et al., 2018; Benhemma-Le Gall et al., 2021) and that porpoises leave the area completely or only reappear 8 to 20 min after the approach of a ship (Frankish et al., 2023; Oakley et al., 2017; Roberts et al., 2019). We can expect that frequent close ship passages acts as an accumulation of disturbances over time and have a more pronounced effect on the distribution of porpoises.

The number of vessels and proximity to maritime traffic could, in some cases, be better proxies of the ship disturbance than the prediction of vessel sound levels. This is especially the case over large areas, where the complexity of environments and the large amount of data to be processed involve uncertainties in the received sound levels.

4.3. Strong effects in areas with heavy shipping traffic may mask the effects of isolated, occasional ship disturbances such as high-speed pleasure crafts

We suspect that major, long-lasting disturbances in areas of heavy commercial traffic, such as the English Channel, have stronger impacts on porpoise distribution and were therefore given more weight in the models than isolated, occasional ship disturbances. Occasional disturbance may trigger, nonetheless, behavioural and negative physiological responses as reported in previous studies (Frankish et al., 2023; Wisniewska et al., 2018; Dyndo et al., 2015), possibly leading to health effects on population level. Disturbance in important foraging grounds could have critical effects (Gallagher et al., 2021) on harbour porpoises and might cascade through the food web, possibly affecting other species via direct and indirect effects. Further research is required in this field.

Hao et al. (2024) found that harbour porpoises reacted to the speed of recreational ships but quickly resumed their natural behaviour once the ship had passed. The effect of vessel speed was also negatively correlated with the number of harbour porpoises in our analysis, but the effect magnitude was lower than those of the number of vessels and the average distance of closest approach. Small-sized, high-speed pleasure crafts, which produce high-frequency noise that is known to disturb porpoises (Wisniewska et al., 2018; Dyndo et al., 2015), often lack AIS transmitters (Nachtsheim et al., 2023) and limit the model capacity to explain porpoise distribution based on vessel speed. This will mainly affect coastal areas, where AIS bearing ships may constitute as little as 17 % of the total ship traffic in the Baltic Sea (Hermannsen et al., 2019), making AIS a poor proxy for ship disturbance in these areas (Hao and Nabe-Nielsen, 2023).

5. Conclusion

Our broad-scale analysis of the impact of maritime traffic on harbour porpoise distribution in the North Sea shows that porpoises avoid areas heavily used by ships. Our analysis yielded superior outcomes considering the average disturbance over time instead of considering only the highest disturbance. Furthermore, our analysis showed that frequent vessel approaches and high numbers of ships had significant negative short-term effects, which were higher than might be expected from the predicted sound levels. This discrepancy may be attributed to uncertainties in predicting sound levels or other factors disturbing harbour porpoises. This suggests that the prediction of sound levels alone at a large scale may not necessarily be the best indicator of maritime traffic disturbance for harbour porpoise distribution. These results are valuable for marine spatial planning, particularly given the expected increase in maritime traffic, including construction and service vessels for offshore wind farms, which may further impact harbour porpoise distribution.

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CRediT authorship contribution statement

Rémi Pigeault: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Andreas Ruser:** Writing – review & editing, Visualization, Validation, Software, Methodology, Investigation, Data curation, Conceptualization. **Nadya C. Ramírez-Martínez:** Writing – review & editing, Methodology, Formal analysis, Data curation, Conceptualization. **Steve C.V. Geelhoed:** Writing – review & editing, Data curation. **Jan Haelters:** Writing – review & editing, Data curation. **Dominik A. Nachtsheim:** Writing – review & editing, Methodology, Data curation. **Tobias Schaffeld:** Writing – review & editing, Methodology. **Signe Sveegaard:** Writing – review & editing, Data curation. **Ursula Siebert:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Anita Gilles:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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