Measurement of effects of pile driving in the Borssele wind farm zone on the seals in the Dutch Delta area version II

Changes in dive behaviour, haul out and stranding of harbour and grey seals

Author(s): Sophie Brasseur, Geert Aarts, Jessica Schop

Wageningen University & Research report C059/22

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Measurement of effects of pile driving in the Borssele wind farm zone on the seals in the Dutch Delta area- version II

changes in dive behaviour, haul-out and stranding of harbour and grey seals, including sound modelling

Sophie Brasseur, Geert Aarts, Jessica Schop

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Attn.: Aylin Erkman
Postbus 556
3000 AN Rotterdam

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Photo cover: Aerial picture of the tagging of seals in the Delta 19-09-2019. Pim Wolf (Delta Milieu Projecten)

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Summary

On the long term it is to be expected that mobile marine animals will be influenced by the intended large-scale changes planned in the Dutch marine waters, being primarily the construction and operation of windfarms. Some scenarios forecast that ultimately approximately 25% of the Dutch part of the North Sea might be covered by wind farms. These constructions, supported by significant rise in ship traffic to build and service the windfarms but also support supplemented activities, encompass significant changes in the marine habitat. Moreover similar intentions have been declared by the other North Sea countries. The ecological effects of these changes are still unknown, and the WOZEP (Wind Op Zee Ecologisch Programma) aims to provide insight in these potential effects.

In this study 10 harbour seals and 10 grey seals were tracked to study the effects of pile driving in the Borssele wind parks (1-4) near the southern Dutch border on the seals' behaviour. Additionally, long term monthly counts of seals on land (data provided by Delta Milieu Projecten; DMP) and records of stranded animals (collected by volunteers and seal rescue centres, available on waarneming.nl) were inspected to detect changes in trends. In addition to the study directly commissioned by the WOZEP programme of RWS (Borssele 1: Brasseur *et a.l* in press), where effects were studied based on distance, we also studied the effects based on modelled sound exposure levels. In this rapport the complete results are presented. For this second study we were subcontracted by TNO, in a project commissioned by the WOZEP programme.

Changes in dive behaviour: Despite the closeness of the Borssele wind farms to the seal colonies in the Delta area, very few seals ventured in proximity of the construction site. The closest observed exposure to pile driving was at 8 km from the construction site. This harbour seal started changing diving behaviour before pile driving commenced. The grey seal closest to a pile driving event was observed at 12 km. It significantly declined in descent speed once pile driving started, indicating a switch from foraging to more transitory movement. Further away, from 14 km onwards, the responses were more ambiguous, with some individuals showing no apparent response, but some revealing a response even at a distance of 29 km. Compared to the previous studies (i.e. Luchterduinen and Gemini), the distances at which seals demonstrated changed behaviour appear smaller. This might be the result of mitigation (bubble curtains) used to reduce sound exposure levels. There is a risk that the mitigation measures are not 100% effective, and this may explain the occasional behavioural responses at distances similar to those observed during the construction of Gemini and Luchterduinen wind park. The ability to study the behavioural response to the Borssele pile driving was very limited. This is mostly due to low number of seals in proximity of the pile driving site, partly caused by an observed avoidance of the area. See the distribution analysis for more details.

Changes in relation to sound exposure levels: Mostly due to the mitigation measures, the single strike Sound Exposure Level (SEL) values are relatively low. During the study the highest estimated SEL for a seal exposure was 144 dB re 1 $\mu Pa^2 s$, which corresponds to a frequency weighted SEL of 129 dB re 1 $\mu Pa^2 s$. Very few exposures were above 130 dB re 1 $\mu Pa^2 s$ (unweighted), which is the region where clear behavioural responses are expected. Due to the low number of seals in the vicinity of the Borssele wind farm area, no significant relationship between changes in dive descent speed and SELs was found. The data from the Borssele area alone was therefore also insufficient to estimate a dose-response relationship.

Changes in distribution in relation to construction at the Borssele site: The low number of exposures at close range (thus higher single strike SELs) might be due to a general avoidance of the wind farm area. Indeed, the tracking data show low seal density in the wind farm area, though this could be unrelated to the wind farm area (i.e., unfavourable environment). For that reason, a habitat model was developed, disentangling the effect of the wind farm from other environmental variables. For harbour seals, close to the wind farm site (up to approximately 10 km) the model estimates lower densities than expected based on the habitat characteristics, suggesting an avoidance of the site. For

grey seals, no significant effect was found. It should be noted that sample size was low, with only 10 harbour and 10 grey seals tracked during the Borssele 1-4 construction phase. Therefore, it is advisable to repeat the analysis using tracking data from regions in the vicinity of all other wind park areas.

Counts: Both grey and harbour seal colonies in the Delta area are recovering from centuries of hunt and disturbance. Numbers counted and trends are mostly influenced by animals migrating in and out of the area to feed, rather than local population growth through births. Compared to a model describing for both species the annual and seasonal trends in counts, the observed numbers of seals on land during the Borssele construction period changed in most of the sub areas. However, these changes were not consistent throughout the different sub regions and the two species. Harbour seal numbers were generally lower in the Voordelta than expected while in the inner waters, they were higher. As in former years, grey seals were mostly concentrated on one single haul-out site in the northern part of the Voordelta however, contrary to more southern haul-outs, and compared to the population model, unusually high numbers were recorded here on land in 2021. These results suggest that seals either avoid the area or, in the case of the grey seals, spend more time on land to avoid being in the water where sound is louder. Alternatively, more seals on land could indicate that perceived conditions elsewhere, for example in the United Kingdom or Wadden Sea area are less favourable than the Voordelta.

Strandings: Compared to the preceding years, more dead seals were found on the coasts in the Delta in 2020 and 2021, the two years following the pile driving. This was mostly the result of young animals (pups and subadults) found, especially harbour seals. The current stranding records are not necessarily consistent and lack for example length and weight of the animals and no necropsies are carried out, leaving the cause of death unrevealed.

Concluding: Behavioural changes, avoidance and changes in seal numbers hauled out and stranded were observed that coincided with the pile driving, however, many other (unrecorded) activities were also going on in the area, confounding the effect pile driving in Borssele. Further studies should take this into account and, like ecological monitoring, human activities should be recorded in detail. Potentially, the records of the windfarms constructed in the North Sea 2005-2022, provide an opportunity for a more holistic approach to study their effect on changes in distribution of seals on an ecological scale (both spatially and temporally) relevant for the population. By combining all available data (both seal tracking and wind farm construction data), using for example similar methods to the habitat model, it will be easier to distinguish the effect of pile driving from other confounding anthropogenic activities or natural processes.

1 Introduction

1.1 Background

For the transition towards renewable energy, the Dutch government has chosen to support large scale construction and exploitation of windfarms at sea. In 2050 all energy used in the Netherlands must come from renewable sources. In 2021, the capacity of offshore wind power in the Netherlands was approximately 2.5 gigawatts (GW) (https://www.government.nl/topics/renewable-energy/offshore-wind-energy). According to the current plans by 2030, this should have grown to 11GW, and depending on the different scenario's, by 2050 the Netherlands should have an off shore capacity of 38-72 GW, respectively fifteen or almost thirty times the capacity in 2021, and some scenarios suggest that approximately 25% of the Dutch North Sea will be allocated to wind parks (Matthijsen *et al*., 2018). These changes will also lead to significant rise in ship traffic, to build and service the windfarms, but also support supplemented activities, leading to even greater changes in the marine habitat.

Despite the perceived urgency, there is relatively little knowledge on the effects of these projects on the North Sea ecosystem, though several reviews of the potential impacts of offshore wind energy on marine species have been drafted e.g. (Inger *et al.*, 2009; Boehlert and Gill, 2010; Verfuss *et al.*, 2016). The WOZEP program (Wind Op Zee Ecologisch Programma), commissioning this study aims to reduce this gap. The lack of understanding holds for many of the short-term consequences and certainly for longer term and population effects on the species inhabiting the North Sea. At least locally, sessile organisms will be affected in the process of construction. Also, given the sandy or muddy bottoms in the southern North Sea, the new hard substrate could facilitate the occurrence of some species in favour of the ones currently resident. For flying organisms, like birds or bats, the rotating wind turbines could inflict some direct mortality. For marine mammals, the underwater sound produced during the construction and operation of wind farms, could affect the hearing either temporarily or permanently, depending on the proximity to the sound source and the duration of the exposure. These activities, but also increased vessel traffic or other related activities (for example sonar inspection, explosion of unexploded ordnance) could cause displacement and changes in behaviour in mobile marine animals. Indirectly, the physical presence of offshore windfarms and activities may lead to changes in prey communities, affecting the predators' food availability. The behavioural changes can potentially result in effects on the animals' fitness, especially if large proportions of the marine areas are disturbed (Aarts *et al*., 2016a; Joy *et al*., 2018; Kauhala *et al*., 2019; Ashley *et al*., 2020; Sinclair *et al*., 2020; Keen *et al*., 2021).

It is relatively complicated to study these effects in most marine animals as they remain obscured under water. However, seals can be considered exceptional in this matter as they are, like most marine species, completely dependent on the marine environment for food and mobility, while they periodically come back to land where they can readily be observed and counted, resting, moulting or breeding (Brasseur *et al.*, 1996; Ramasco *et al.*, 2014). For many pinniped species long term population monitoring enables detailed trend analysis and estimates of pup production (Meesters *et al*., 2009; Brasseur *et al*., 2015; Brasseur *et al*., 2018d; Thomas *et al*., 2019; Galatius *et al*., 2021; Sigourney *et al*., 2022).

As the most intense single sound during construction is considered to be the pile driving, most studies have been commissioned to study only the effect of pile driving. The current study on the effect of windfarm construction near the southern Dutch coast (the Borssele windfarm zone), is again focused on pile driving and direct effects on behaviour, though efforts are made to also look at changes in spatial distribution at sea and in number of seals on land and strandings, using existing data sets.

1.1.1 Seals in Dutch Delta Waters

In the Dutch Delta area, south of Rotterdam, harbour and grey seals have relatively recently started to recover from centuries of hunting, habitat destruction and disturbance (Dedert *et al*., 2015). Nowadays seals can regularly be seen laying (hauling out) on tidal sandbanks along the coast. Most animals observed in the Delta area do not reproduce locally, but visit the surrounding waters to feed, while migrating annually back to the Wadden Sea or the United Kingdom (UK) to breed (Brasseur *et al*., 2016; Brasseur, 2017; Brasseur *et al*., 2018c). Original harbour seal breeding colonies were destroyed in the 20th century, initially as a result of hunting and pollution, and followed by the construction of the storm protection in the area (*Deltawerken*). In fact, between 1970 and 1990 harbour seals were practically absent from the area. When the construction was finalised, harbour seals gradually returned. In addition, the grey seals that had been absent for centuries started to repopulate the area. Though still small, there are new breeding populations of both species, in the Wester and the Oosterschelde (See chapt. 2.5 and 0. for more detail on population developments).

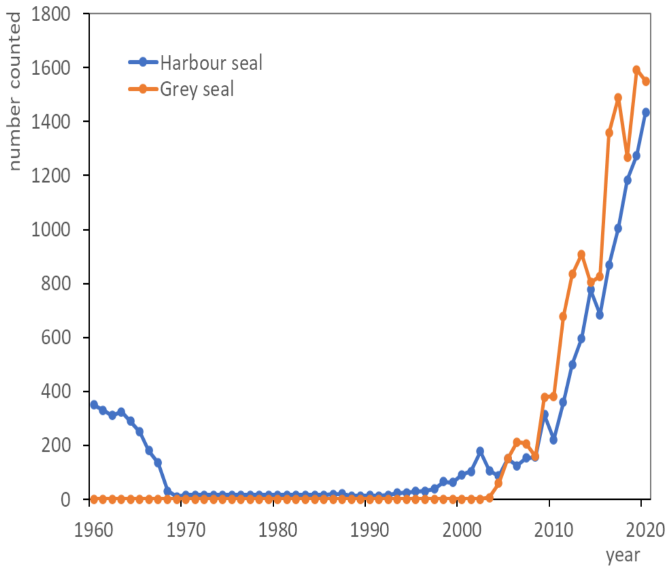


Figure 1. Development of the number of seals counted in the Dutch Delta area 1960-2021 (data: Compendium voor de Leefomgeving (clo.nl))

1.1.2 Underwater sound and other potential effects

As mentioned before one of the most intense single sound sources in offshore wind farms is probably pile driving during construction, and most studies are only directed to this construction phase. However, a (single) pile driving event only lasts for a few hours. Other activities may have lower sound exposure levels, including increased vessel traffic, (pre-) construction or operation, but last longer. These long-term effects have hardly been studied.

The sound produced as a result of pile driving of offshore windfarms typically peaks between 0.1 kHz and 1 kHz, which fall within the hearing range of the harbour and grey seals (Kastelein *et al.*, 2013; Reichmuth *et al.*, 2013; Ruser *et al.*, 2014; Kastelein *et al.*, 2015; Cunningham and Reichmuth, 2016; Lucke *et al.*, 2016; Kastelein *et al.*, 2018a; Kastelein *et al.*, 2018b). The sound levels and frequency may vary depending on the technical specifications of the pile and hammer and for instance mitigation. Sound perceived by the seals will typically depend on the distance to the source and environment (bathymetry, bottom type etc., but also wave action for example).The seals are capable of hearing the sound at large distances. A study in the UK demonstrates avoidance behaviour of harbour seals in an area of 40 km away from the pile driving site (Russell *et al.*, 2016). This distance is equivalent to the distance at which in average behavioural changes were measured in grey seals in the proximity of pile driving in the Netherlands (Aarts *et al*., 2018). There was however large individual variation, with behavioural changes observed between 10 and 50 km away from the pile driving site. The construction sites in previous studies (Luchterduinen en Gemini), were respectively

40 and 60 km away from haul-out sites. The piledriving in the studies above was not mitigated. The construction of windfarm Borssele is only ~20 km away from important harbour and grey seal haul-outs in the Dutch Delta, and thus provided for a unique opportunity to study behavioural changes of the seals using the area. However, for pile driving on the Borssele sites, bubble curtains were used as a mitigation measure, dampening sound and therefor potentially attenuating the distances at which seals could be affected (Stöber and Thomsen, 2019).

1.2 Expected effects on seals

It is unlikely that seals will directly be killed during pile driving, as density at sea is rather low and prior to pile driving the seals present would be assumed to avoid the busy area, potentially escaping sound levels that could cause mortality. Some animals could suffer permanent or temporary hearing loss, but deterring devices (ADD), and ramp-up procedures in piling intensity and other mitigation measures, are set up discourage animals to come too close (Heinis *et al*., 2019). However, animals traveling or feeding anywhere within hearing range of the pile driving, could be driven to change their behaviour as was demonstrated in several studies (Hastie *et al*., 2015; Aarts *et al*., 2018; Hastie *et al*., 2019). As sound propagates well in seawater, pile driving could be audible to seals at tens of kilometres, potentially impacting hundreds of individuals. For example, based on Aarts *et al.* (2016b) at an average seal density of 1 seal/km^2 sound being audible at a distance of 15 km could influence more than 700 individuals, and at 30 km, the behaviour of approximately 2800 individuals could be impacted. Seals often show site fidelity to their feeding areas, and are more likely to be exposed to such disturbances for longer periods compared to migrating animals.

Although proof of direct or long term effect on health, fitness or ultimately survival, is difficult to obtain, there are indications that these could all occur (Kunc *et al*., 2016). Potentially some indications of effects of the construction on the seal colonies along the Dutch coasts could be found in:

1. Changes in *behaviour* (e.g., at sea diving and movement), *especially during construction*.
2. Changes in *distribution* due to avoidance of the area (reflected on land in changes in numbers of grey and harbour seals hauled out in the Delta area)
3. Changes in *health* (e.g., body condition)
4. Changes in the *vital rates*, like reproduction (numbers of pups) and mortality (e.g., reflected in number of stranded animals)

On the longer term, all these changes could lead to changes in population size and the role of seals as top-predator in coastal ecosystems.

1.3 Research questions

In the frame of WOZEP two projects were consecutively mounted around the same seal tracking data, the Borssele 1 research project (Brasseur *et al.* in press) and the Borssele 2 research project (this study). The first study concentrated on the movements and distribution at sea, and haul-out counts, and stranding of seals in the Delta area. In the second study, estimates of sound exposure were available, allowing us to link the seals' behaviour to specific sound levels rather than distance. Because these two studies are so tightly interlinked and cannot be presented in isolation, the results of both projects are presented in this report.

In the Borssele 1 project, seals were tracked with the aim of observing potential behavioural changes in relation to the pile driving activities of the companies Ørsted and Blauwwind in the Borssele wind farm area. In addition, existing monitoring of the number of seals hauled out in the Delta area and records of strandings were studied to evaluate potential effect at the larger scale. This project was commissioned directly by WOZEP. Specific research questions were:

1. How are the individual harbour and grey seals affected in their behaviour by the underwater sound caused by the pile driving of the wind turbines? What are the observed changes in behaviour?
2. At what distances can a change in behaviour be observed and how big are these changes?
3. Are the behavioural changes dependent of the context, such as the status of the animal, which phase of the foraging cycle the animal is in, etc.?
4. What consequences can these behavioural changes have for the condition and fitness of the individuals?
5. What are the effects on the number/distribution of animals on the haul-outs, can this be related to the behaviour of the tagged individuals?
6. What is the effect of mitigating measures?

In the project Borssele 2, the seal analysis was extended by studying the relationship between dive behaviour and sound exposure level. This extension was embedded into an ongoing project lead by TNO combining work from WaterProof, WMR, and TNO. The aim of the study was also to investigate the effects of the construction sound on porpoises (Jong *et al*., 2022). In this research project, a sound propagation model (Aquarius 4) was developed and implemented for both porpoises and seals. This provided for the possibility of relating behavioural changes of GPS tracked seals to (modelled) sound levels rather than only distance to the source. This project was subcontracted under TNO and commissioned by WOZEP. The following research questions were defined:

7. At what sound level can a change in dive behaviour be observed? How does this change in relation to the calculated acoustic measures (SELss, SELss,w and SPLw) at the track locations? Which measure (SELss, SELss,w, SPLw or distance) is best used to do so?
8. Can a Dose-Response curve be defined based on the available data? In other words: Can changes in behavioural states (e.g. foraging, resting, exploring and transit/swimming) be related to changes in sound levels or distance to the pile driving?

The latter additional question was formulated, but was eventually discontinued. During the analysis of research question 7 it became clear that it could not be addressed as the number of animals in the vicinity of the construction site were too low, possibly due to avoidance of the piledriving area. This is discussed in the results presented in 3.5.

From previous studies (Brasseur *et al*., 2018a; Brasseur *et al*., 2018b), there were indications that seals avoided wind farm areas during the construction and operational phase. The dive analysis, designed to capture changes in relation to activities can only be performed for those animals that are in the vicinity of the piling location at the start of the piling session. However, it is possible that animals avoid the area during the entire construction phase. The animals that stay and continue to use the area could be naturally less sensitive to disturbance caused by pile driving. Therefore, using a habitat model as described in Aarts *et al*. 2016, in which distance to pile driving is included as an explanatory variable (comparable to an analysis as described by Russel *et al* (2019)), changes in dispersion during the construction period are studied. Therefore, the following research question was added

9. Does the distribution of seals change in relation to the pile driving?

1.4 Construction in the area

The Borssele wind farm zone, off the coast of Zeeland, is occupied by two wind farms exploited by the companies Ørsted and Blauwwind (data from https://www.noordzeeloket.nl/ n/functions-and-use/offshore-wind-energy/free-passage-shared-use/borssele-wind-farm-zone/). Both windfarms each have two building sites (Borssele 1&2 and Borssele 3&4 respectively; *Figure 2*). Additionally, there is an “Innovation site” exploited by Two Towers. The electricity is brought to land near Borssele by transmission cables and, from there, distributed to the national high voltage network. Minimum distance to shore is approximately 22 km and when conditions are clear, the wind farm can be seen from Westkapelle.

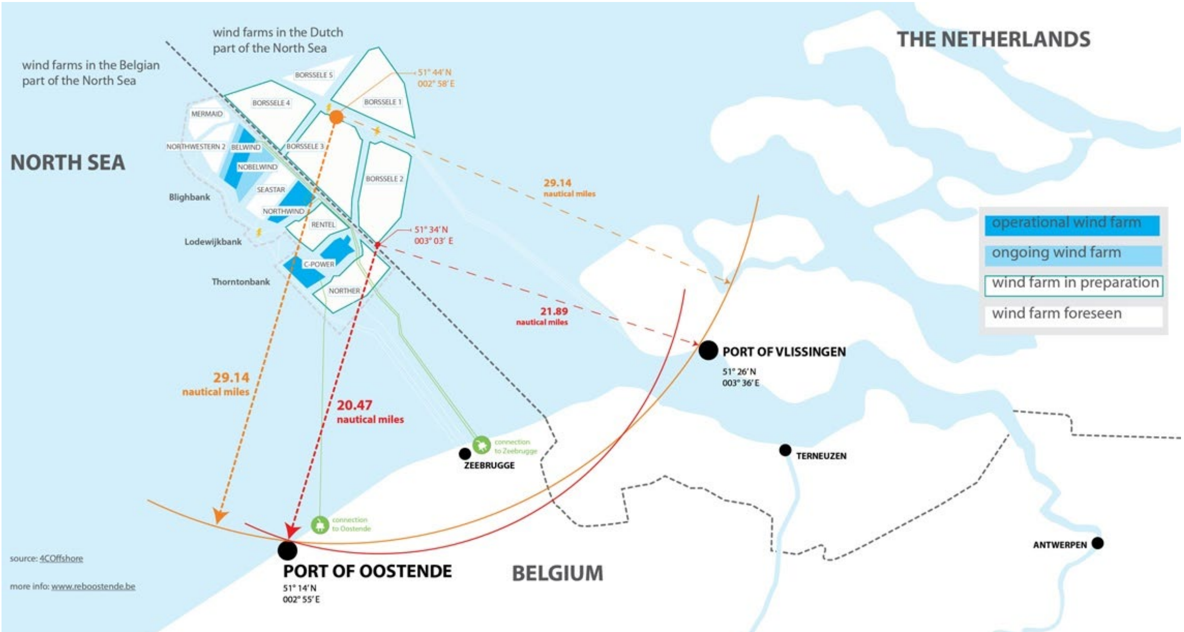


Figure 2. (https://deepresource.wordpress.com/2020/01/14/first-monopiles-installed-at-borssele-offshore-wind-project/)

The Borssele area is adjacent to the Belgian windfarm zone, which has been in construction since 2007, including the latest sites of which the pile driving overlaps with the Dutch wind farms (see also 2.1.2). The total zone currently developed for windfarms (Dutch and Belgian) covers an area of over 600 km^2

Compared to other existing wind parks, this is a relatively large area. For example, to the north, the *Luchterduinen* park was built in 2015 and occupies only an area of 25 km^2 (Kirkwood *et al.*, 2014; Kirkwood *et al.*, 2015; Kirkwood *et al.*, 2016; Brasseur *et al.*, 2018b). Also, by 2020 preparations were ongoing for the construction in 2021 of another large park north of the area, *Hollandse Kust Zuid*, extending across an area of 235.8 km^2 (https://www.power-technology.com/projects/hollandse-kust-zuid-wind-farm-north-sea/). It is common that pre-construction commences 1,5- 2 years in advance. This for example involves seismic surveys to classify sea floor structure and detect unexploded ordinances, the detonation of such explosive, and placement of power cables and construction of power distribution hubs. It is likely that also during the tracking of the seals in 2019-2020 such activities took place. However, no data on these activities were provided.

2 Material and methods

2.1 Data

For this report different data sources were used. An overview is provided (for the period 2018-2021) of when construction occurred and when seal data were collected (Table 1). For both species three types of data were collected: the tracks and dives of seals, seal counts collected by DMP and stranding records of dead seals made available via waarneming.nl. Sound measurements were made in the period November 2019 - September 2020 (Jong *et al*., 2022).

Table 1. Overview of the timing of construction and data collection between 2018 and 2021. Blue, red, purple and green boxes indicate ongoing activity (indicated in the left column); grey and white the absence of such.

	Jul - 2018	Aug - 2018	Sep - 2018	Oct - 2018	Nov - 2018	Dec - 2018	Jan - 2019	Feb - 2019	Mar - 2019	Apr - 2019	May - 2019	Jun - 2019	Jul - 2019	Aug - 2019	Sep - 2019	Oct - 2019	Nov - 2019	Dec - 2019	Jan - 2020	Feb - 2020	Mar - 2020	Apr - 2020	May - 2020	Jun - 2020	Jul - 2020	Aug - 2020	Sep - 2020	Oct - 2020	Nov - 2020	Dec - 2020	Jan - 2021	Feb - 2021	Mar - 2021
	ESTIMATED CONSTRUCTION PERIOD (light blue) INCLUDING PILE DRIVING (X)																																
Ørsted (NL)																			X	X	X	X	X										
Blauwwind (NL)																X	X	X	X	X	X	X											
Seamade (B)														X	X	X	X	X															
Northwester 2 (B)													X	X	X	X	X																
Rentel (B)		x?	x?	x?																													
Norther (B)						x?	x?	x?	x?																								
	DATA COLLECTION																																
Tracking Grey seals																																	
Harbour seals																																	
Sound measures																																	
Seal surveys					*										**		*										**		*	*			
Strandings																																	

Surveys counting seals: *=incomplete; **= financed by the project Borssele I

2.1.1 Tracking data

Trackers were deployed on 20 seals in the coastal zone West of the Grevelingen in the Dutch Delta area, south of Rotterdam (area -3_VD_G, *Figure 6*). Ten harbour seals were captured on 18-09-2019 on a sandbar just north of Renesse (51.75°N, 3.75°E). The ten grey seals were captured the following day on 19-09-2019 from a sandbar west of Ouddorp (51.79°N, 3.78°E).

Table 2. Overview of grey seal (Halichoerus grypus) and harbour seal (Phoca vitulina) deployments in the Dutch Southern Delta in the frame of the Borssele project.

	n	Avg. length (m)	Avg. weight (kg)	End date	Min duration (days)	Avg. Duration (days)	Max duration (days)
grey seals	**10**	**179**	**97**	**14/03/2020**	**35**	**103**	**177**
FEMALE							
adult	4	173	94	01/02/2020	97	115	135
MALE							
adult	4	199	122	14/03/2020	35	102	177
subadult	2	152	54	21/12/2019	73	83	93
harbour seals	**10**	**141**	**44**	**08/02/2020**	**23**	**104**	**143**
FEMALE							
adult	1	141	43	07/01/2020	111	111	111
subadult	2	128	29	08/02/2020	123	133	143
MALE							
adult	4	158	59	20/01/2020	78	97	124
subadult	3	126	36	28/01/2020	23	94	132

Seals were captured at low tide near sandbars using a purpose-built seine-net of approximately 100 m length and 8-m drop. Healthy individuals that had completed their moult were selected to carry transmitters. We attempted to get an even spread of males to females and sub-adults to adults. For adult grey seals, the nose-to-tail lengths were >140 cm for females and >160 cm for males. For adult harbour seals the nose-to-tail lengths were >135 cm for both females and males. Selected seals were strapped into purpose-built cradles and had the transmitter glued (Loctite) to their pelage at the mid-dorsal point behind the neck. While the transmitter was glued, the length, weight and sex of the seal was determined. Once the glue had set, each seal was released and, upon release seals proceeded directly to the water. All seals were released within 90 min. of capture.

Seals were tracked using GPS-GSM transmitters (weight app. 330 g in air, volume 150 cm^3) from the Sea Mammal Research Unit (SMRU, St Andrews, Scotland). These transmitters contain a Fastloc®GPS, pressure sensor to measure dive depth, wet-and-dry sensor to measure the start and end of haul-out events, and temperature sensor to measure ambient sea water temperature. The Fastloc® GPS in the transmitter attempted to determine a location after a pre-set interval and when the antenna was next exposed. To maintain battery life throughout the sample period, the sample interval was set at 15-minutes. Seal location and dive data were transmitted from the tracking devices via the GSM-network, when the animals were hauled out.

All required permits were obtained. This included a permit under the Flora and Fauna Act (*Flora en Fauna Wet*) from the Dutch government, to handle the seals as protected animals, permits under the Dutch Nature Protection Act (*Natuurbeschermings Wet*) from the provinces of Zeeland and Zuid-Holland to enter and work in the capture areas, and protocols approved by an animal ethics committee (*Dier Ethische Commissie, DEC*) of WUR.

2.1.2 Pile driving and description of construction activities

Initial aim of the project was to study the effect of the pile driving of the two Dutch windfarms exploited by *Ørsted* and *Blauwwind* (**Error! Reference source not found.**). The pile driving phase for these Borssele parks lasted from 23 October 2019 to 20 April 2020 (*Borssele 3 & 4 – Blauwwind*) and from 8 January 2020 to 2 June 2020 (*Borssele 1 & 2 - Ørsted*). During these almost 8 months where the pile driving phases overlapped partially, a total of 172 monopile bases were pile-driven into the seabed for the Borssele projects. This work was preceded and also overlapped with the construction of two Belgian parks (*Seamade* and *Nothwester*) in the adjacent area (see Table 3 for details). Moreover, yet two other parks were in construction (*Rentel* and *Norther*) shortly before, though there are no pile driving details available for these two parks. Also, by 2020 preparations were ongoing for the construction of *Hollandse Kust Zuid,* but unfortunately no seal tracking data were available for this period and region. The consecutive constructing of all these parks will have consequences for the interpretation of the data as effects could accumulate over time.

*Table 3. Overview of windfarms constructed in the Borssele area 2017-2020. Parks for which pile driving details were available are indicated with an *.*

Wind Farm	Rentel	Norther	Northwester*	Seamade*	Borssele 3& 4 – Blauwwind*	Borssele 1 &2- Ørsted*
Country	Belgium	Belgium	Belgium	Belgium	Netherlands	Netherlands
Lat	51.59	51.53	51.69	51.68	51.70	51.68
Lon	2.94	3.01	2.75	2.80	2.93	3.07
start	2017	2018	2018	2019	2019	2020
commissioned	2019	2019	2020	2020	2021	2020
pile start	no data	no data	29/07/2019	08/09/2019	23/10/2019	08/01/2020
pile end	no data	no data	13/11/2019	02/01/2020	20/04/2020	02/06/2020
Min Depth (m)	24	13	25	20	14	16
Max Depth (m)	34	26	37	27	38	38
Area (Km^2)	23	38	12	35	61	56
Num Turbines	42	44	23	58	78	94

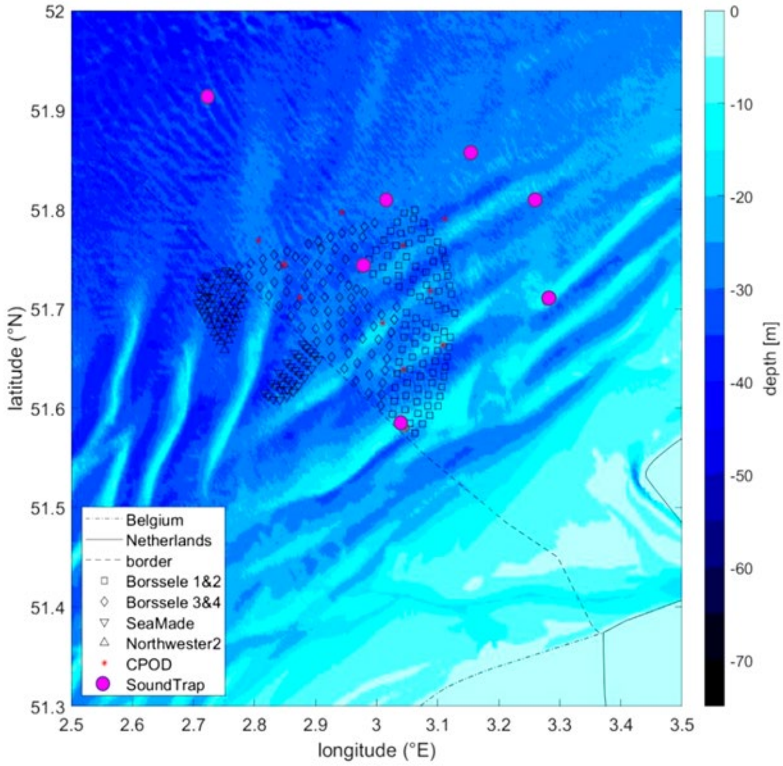


Figure 3. Map showing position of piles of Northwester, Seamade, Borssele 3 & 4 (Blauwwind) Borssele 1 &2 (Ørsted) and the location of the seven Sound Traps ((Jong et al., 2022))

This study was initially designed to only study the effect of pile driving of the two Borssele wind farms. As it became clear that the seal data also overlapped with the pile driving of the Belgian parks, information on pile driving of these parks were added to this study. Pile driving data was provided by Orsted, Blauwwind en RBINS and structured in a database by the company WaterProof.

Table 4. overview of duration of ADD (minutes), Bubble curtains (minutes) and pile driving (hrs:min:ss)

	Borssele 1&2	Borssele 3&4		Northwester	SeaMade		AVERAGE
Bubble curtain	*HSD+DBBC*	*AdBm + DBBC*	*DBBC*	*DBBC*	*DBBC*	*DBBC*	
Min ADD before	26.88	29.00	40.00	32.00	24.00	42.00	24.00
Average ADD before	39.24	100.75	80.76	66.00	40.17	103.50	59.09
Max ADD before	90.30	944.00	190.00	342.00	185.00	165.00	944.00
Min ADD after	-7.40	-320.00	0.00	-253.00	-149.00	-188.00	-320.00
Average ADD after	2.22	-2.10	2.44	-148.92	-72.34	-130.00	-30.86
Max ADD after	38.45	12.00	6.00	-89.00	45.00	-72.00	45.00
Min BBC before	-0.47	-6.00	3.00		-2.00		-6.00
Average BBC before	26.13	18.92	17.60		22.90		22.74
Max BBC before	92.30	90.00	42.00		171.00		171.00
Min BBC After	-3.00	0.00	0.00		1.00		-3.00
Average BBC After	6.54	5.04	4.60		6.76		6.04
Max BBC After	38.93	30.00	19.00		21.00		38.93
Min duration Pile driving	01:39:00	01:58:00	02:31:00	02:11:00	01:35:00	01:57:00	01:35:00
Average duration Pile driving	02:05:44	04:05:35	03:41:10	03:51:30	02:18:22	03:57:30	02:53:14
Max duration Pile driving	04:57:00	21:21:00	06:51:00	11:48:00	04:43:00	05:58:00	21:21:00

Prior to each pile driving event, underwater sound produced during the installation of the pile driving vessel and monopile may have been detected by seals. For example, before each monopile was pile-driven, the vessel was positioned using active sonar, jacked-up, and an acoustic deterrent device was switched on. The deterrents generally produce sounds at frequencies anticipated to be at, or just above the seals optimal hearing and might be detected by seals within hearing range. In all parks deterrent devices were switched on at least 20 mins before pile driving commenced, however in some cases they commenced earlier with a maximum of almost 16 hours. They were often stopped (124/255 piles) before pile driving ended.

After the piling vessel is installed, the monopile is picked up and lowered to the sea-floor and a pile driving hammer was positioned over it. To mitigate the pile driving sound produced, so called *bubble curtains* were used. These differed per park: SeaMade and Northwester indicated using Double Big Bubble Curtain (DBBC) for all 24 piles, though from Northwester and in 2/60 cases from SeaMade no data was provided on when these were deployed. Borssele 1&2 used Hydro-Sound Damper (HSD)+DBBC for all 94 piles and Borssele 3&4 52/77 piles were mitigated using AdBm (another near-to-pile Noise Abatement System) + DBBC, the remaining piles only DBBC was used (see (Bellmann M. A., 2020) for mitigation measures). Though in a few cases, the bubble curtains were started after pile driving started, in average they were started a bit more than 20 minutes in advance.

Once pile driving commenced, hammering was not necessarily continuous. It often commenced with a 'soft-start', i.e., no or light (~200 kJ) power, to ensure the monopile seated correctly and penetrated the substrate in a controlled manner. Initial hammering consisted of one or several blows followed by pauses of up to several minutes for observation/adjustment. As the monopile penetrated further, the frequency, duration and power of hammering increased. In later stages, hammering was at a rate of 40-50 blows per minute for 30 minutes or longer at energy levels >700 kJ. The vessel installed fixtures to the monopile, then jacked-down and moved to the next location. Often, one vessel performed all the pile driving leaving periods of 2-3 days without any pile driving while the vessel restocked. In some cases, two vessels operated in the area, and time-gaps between pile driving events were shorter and occasionally two monopiles were installed simultaneously. Pile driving could also be affected by weather and possibly ceased when wind speed exceeded 15 m/s.

2.2 Sound measurements and modelling

The sound modelling is carried out on the basis of measurements carried out during the construction of the Borssele offshore wind farms. The underwater sound was monitored by seven acoustic recorders i.e. SoundTraps (Figure 3), from November 2019 to September 2020 covering many pile driving sessions, though missing the onset of Northwester, SeaMade and Borssele. Details of methods used and available data were reported in (Oud and de Jong, 2021).

Below a summary directly derived from the harbour porpoise study (Geelhoed in prep).

Following KEC 1.0 (Heinis *et al*., 2015), assumed also in KEC 3.0 (Heinis *et al*., 2019) that the unweighted broadband single strike sound exposure level (SEL_{SS}) is an appropriate metric for the prediction of behavioural disturbance. The SELss levels were modelled using the Aquarius 4 piling noise model (de Jong *et al* 2019), and calibrated using the data from the SoundTrap recorders (within 7,5 km), taking the effect of the mitigation measures into account.

In 2019, (Southall *et al*., 2019) proposed updated auditory weighting functions for assessing the effects of sound exposure on the different marine mammal hearing (permanent and temporary hearing threshold shifts). One of the aims of the present study was to investigate whether the proposed auditory weighting functions are appropriate for quantifying marine mammal behavioural response to sound exposure as well. Because it is unlikely that animals are disturbed by sound outside their hearing range, it is reasonable to take that into account in the assessment of dose-response relationships, by applying some form of auditory frequency weighting.

From a practical point of view, using the same weighted metrics for assessing physiological, auditory and behavioural effects has great benefits. Therefore, the acoustic data in this study are quantified in terms of the following metrics:

Table 5 Overview of metrics considered in this study. The frequency weightings are described in (Southall et al., 2019)

Metric	Description	symbol	unit
SEL_{SS}	Unweighted broadband single strike sound exposure level	$L_{E,SS}$	dB re 1 μPa²s
$SEL_{SS,vhf}$	Broadband single strike sound exposure level, frequency weighted for very high frequency cetaceans (vhf)	$L_{E,\mathrm{SS,vhf}}$	dB re 1 μPa²s
$SEL_{ss\ pcw}$	Broadband single strike sound exposure level, weighted for phocid carnivores in water (pcw)	$L_{E,\mathrm{SS},pcw}$	dB re 1 μPa²s

The SEL_{SS} metrics were determined per piling strike. For the seal study the following data were provided (Oud and de Jong, 2021): calibrated SELss maps on a latitude longitude grid simulated with the Aquarius 4 model corrected for mitigation. SELss are unweighted and pcw-weighted and vhf-weighted (though the latter is not considered relevant for the seals). This was available only for the parks SeaMade, Borssele 1&2, and Borssele 3&4, for Northwester 2 park the hammer blow times and energies are not available.

2.3 Behavioural response analysis of tracking data

2.3.1 Processing seal dive and tracking data

The dive depths measured by the pressure sensor in the tracker were recorded every 4 s, and used to summarize the duration and shape of a dive. The dive duration was defined as the time difference between the first depth measurement below 1.5 m depth and the following first depth measurement above 1.5 m depth. The shape of the dive was summarized by storing depths measurements at the 1%, 2.5%, 5%, 10%, ..., 90%, 95%, 97.5% and 99% time-points of each dive. In contrast to the previous definition of duration of a dive (Aarts *et al*., 2018; Brasseur *et al*., 2018a; Brasseur *et al*., 2018b), the 0% and 100% time-points represented the estimated time the seal crossed the 1.5 m depth line, and hence the time difference between 0% - 100% is on average the dive duration minus 4s.

2.3.2 Seal responses to pile driving – definition of exposures

An exposure is defined as an instance where a seal is tracked during a pile driving event. For each pile driving event, the distance of each animal to the pile driving location was calculated based on the GPS location of the last dive just prior to pile driving. Only those exposures where the seal was within 35 km of pile driving were included in this analysis.

For the remaining exposures, both the GPS and dive data were allocated to a specific period, in respect to the pile driving: 4 h to 5 min. prior to pile driving (t_0), during pile driving (t_c) and 0 to 2 h after pile driving (t_1). The data from the period 5 to 0 min. prior to pile driving were excluded because initial inspection of the dive data suggested that seals sometimes responded a few minutes to seconds prior to pile driving, and it was assumed that this was due to some other pile driving related sound which was not included in the pile driving data. For each dive, the response variables, descent speed was calculated.

2.3.3 Analysing individual-level changes in diving behaviour

Seals often dive to the sea-floor, where they spend 80-90% of the total dive time when foraging. This will lead to a U-shaped dive, with a relatively fast vertical descent (and ascent) speed and a long period of near-constant depth close to the seafloor. When seals are exposed to a disturbing sound source, we expect this pattern to be disrupted. For example, seals may stop foraging near the bottom and attempt to flee away from the sound source, leading to more diagonal movement with slower

vertical descents (and ascents), i.e. a more V-shaped dive. Here, we investigated whether descent speed changed when close to pile driving. The descent speed ($v_{descent}$ in m/s) was defined as the speed between the 1% time-point of the dive and the time-point where the seal reached 80% of maximum dive depth.
For the descent speed $v_{descent}$, we assumed a gamma distribution

$$v_{descent} \sim Gamma(\mu, k)$$
$$\mu = e^{\eta}$$

The linear predictor η was subsequently modelled as a function of the period specific parameters ($\beta_{t_0}, \beta_{t_c}, \beta_{t_1}$) and a temporally correlated smooth:

$$\eta = \beta_{t_0} x_0 + \beta_{t_c} x_c + \beta_{t_1} x_1 + \nu$$
$$\nu = f(t) + \varepsilon$$
$$\varepsilon = Normal(0, \sigma)$$

The values of the variables x_0, x_c and x_1 were 1 when the dive was prior, during or after pile driving, respectively, and 0 elsewhere. The coefficient β_{t_0} represents the log of the descent speed prior to pile driving (t0), and β_{t_c} and β_{t_1} quantify the relative changes (on log-scale) in the descent speed during the pile driving period (tc) and 2 hours after the pile driving (t1), respectively. ν is a temporally correlated auto-regressive term, which captures any correlation in the residuals. When pile driving significantly reduces the descent speed during the pile driving, the parameter β_{t_c} should be significantly smaller than zero.

2.3.4 Analysing population-level changes in diving behaviour

One limitation of the above individual-level statistical inference is that seals regularly change behaviour, and an observed (significant) change in behaviour during pile driving might also be caused by other intrinsic or external stimuli. Likewise, subtle changes in behaviour that are caused by pile driving, might remain un-noticed in such individual-level inferences.
However, when seals do indeed change their behaviour in response to pile driving, we would expect changes in behaviour to occur on average more frequently when seals are close to pile driving. To test this, the estimated $\beta_{t_c}'s$ for each seal and each pile driving event were modelled as a function of the covariate distance to the pile driving (dist):

$$\beta \sim Normal(\mu_{\beta}, \sigma_{\beta})$$
$$\mu_{\beta} = s(dist)_i + \pi_i$$
$$\pi_i = I_i + \epsilon$$

Where s() are smooth functions of the variables. The size of the effect (i.e. β_{t_c}) was allowed to vary by individual using an individual-specific random effect π_i.

2.3.1 Linking sound exposures to seal tracking data

To assess the individual's response to sound exposure level, each exposure event needs to be linked to estimated SEL based on the Aquarius sound propagation model. These SELs vary in space (due to spatially varying propagation relative to the source) and time (as a result of changes in pile-driving intensity). However, for the seals GPS location estimates were not regularly available during many pile driving events, and in some cases, there was only one or even no GPS location during the pile-driving event. Therefore, like the analysis based on distance to the source, we use the GPS location recorded at the time closest to the start of the pile-driving, overlayed these with the SEL maps and extracted the SEL from the overlapping grid cell. The maps of SEL were provided for baseline blow energy intensity of 2000 kJ. Blow energy is continuously changing during the pile driving session. Because diving behaviour during the entire pile-driving session was related to the periods before and after pile driving, these SEL estimate were therefore corrected based on the *average* pile-driving blow energy of that piling session:

$$SEL_{Blow\ energy} = SEL_{2000} + 10log10\left(\frac{Blow\ energy}{2000}\right)$$

A similar extraction was carried out for SELss, SELss_pcw and SELss_vhf. SEL weighted for very high frequency is not relevant for seals, but it provides insight into how a porpoise at similar location would experience sound exposure. *Figure 4* below, shows one example map of SELss (Borssele 1-2, C04).
In some cases, there were two piling events happening at the same time. In that case, the event with the highest SEL at the location of the seal was linked to the seal exposure event.

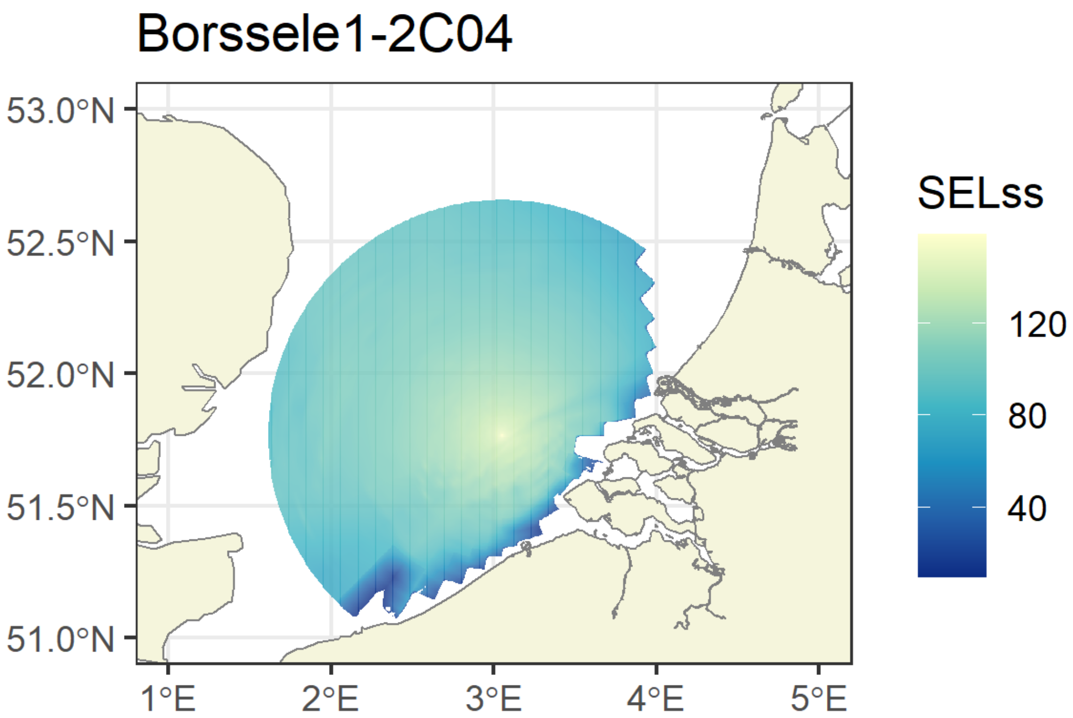


Figure 4. Modelled SELss for the piledriving of monopile C04 (Borssele 1-2) for baseline pile driving intensity of 2000 kJ.

2.4 Distribution analysis based on tracking data

2.4.1 Environmental explanatory variables

Seals are central-place foragers, feeding predominantly near the bottom on benthic prey species. Other studies have shown that harbour seals use areas that are relatively shallow and characterized by sandy substrate (Tollit *et al*., 1998; Sharples *et al*., 2012; Bailey *et al*., 2014; Jones E.L. *et al*., 2015). For that reason, the covariates, distance to haul-out, depth, topographic position index (TPI) and sediment type (%mud) were used (see below and *Figure 5* for more details). Covariates on prey distribution could potentially be used but were of insufficient resolution to capture the fine scale variations in seal density, and hence were not used in this study.

2.4.1.1 Distance to haul-out

Harbour seals are central-place foragers, and foraging sites close to their haul-out sites are therefore more easily accessible. Even if they select areas further offshore to forage, they always must cross the intermediate areas. Consequently, habitat use is expected to be negatively correlated with distance to the haul-out site. Because seals circumvent large sections of land or shallow areas, the shortest at-sea path between each haul-out site and point at-sea was derived. Shortest path calculation was based on a regular grid with varying spatial resolution; a higher resolution (i.e., a point every 200 m) in coastal waters (<10 km from land), and a coarser resolution (i.e., a point every 1 km) further offshore in the North Sea. For each grid point, links were created with the 16 nearest neighbours (function nn2, package RANN (Arya *et al*., 2019). Any link with a land-based point was removed. Based on this, a graph object was created (function graph.data.frame, package igraph; (Csardi and Nepusz, 2006)). The graph object was subsequently used to calculate the path (and distance) of any point within the landscape to each of the 1953 known haul-out sites in the Netherlands, Belgium, Germany, Denmark, and UK. Most of these haul-out sites were derived from aerial surveys and, where necessary, supplemented using data on haul-out events of the tracked seals.
Since calculating the distance to each unique haul-out location (Figure 5) and generating the corresponding availability points would be computationally too demanding, the seal's haul-out locations were first grouped into clusters. This was achieved by applying hierarchical clustering to the distances between all pairs of haul-out locations using the function `hclust` (package = stats, method ="average") and `cutree`, with cut-off distance of d=1km. Next, for each cluster, the distance between the haul-out cluster *c* and each point at sea (taking obstacles into account) was calculated.

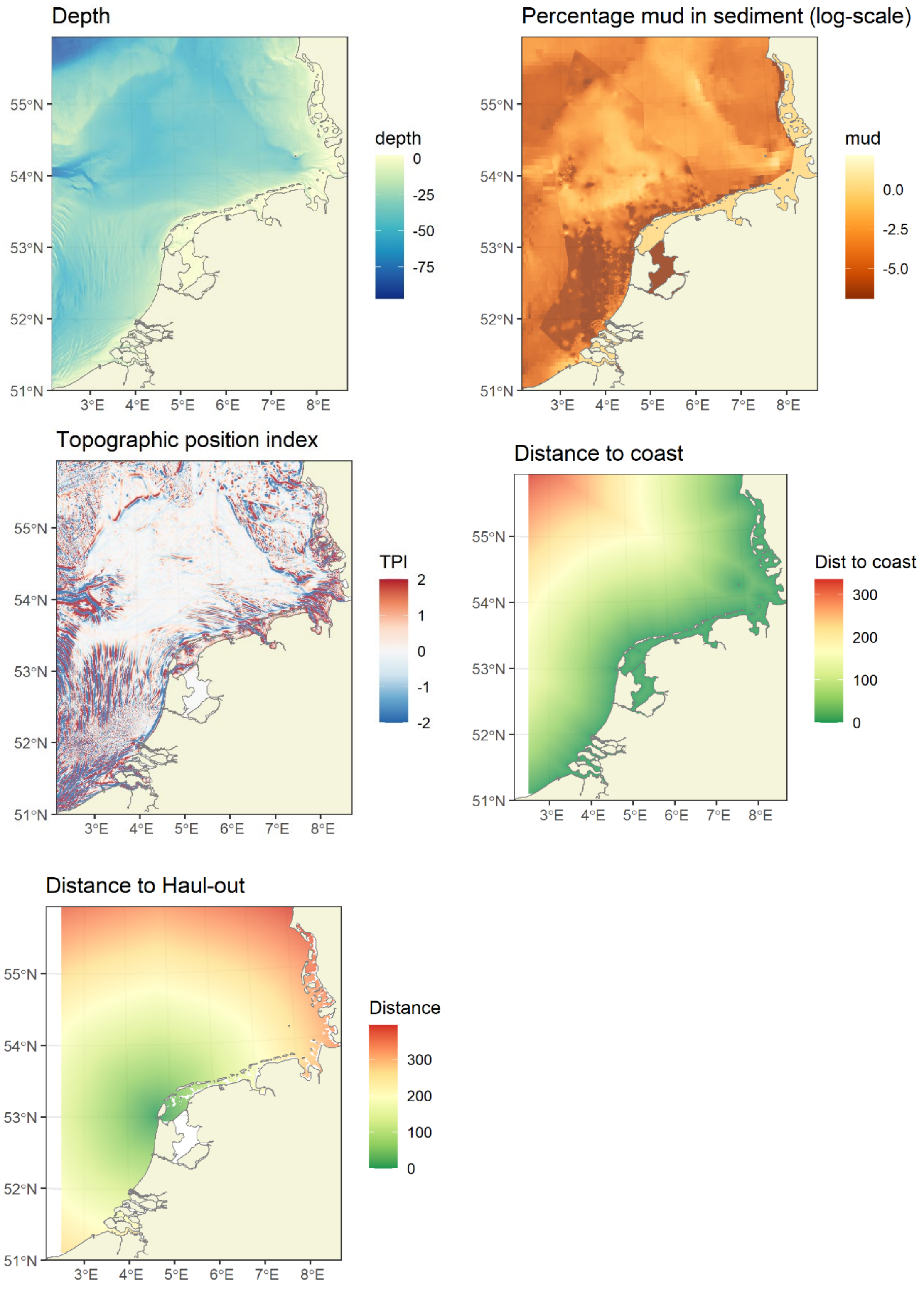


Figure 5. Maps of the explanatory variable Depth, %mud in the sediment, topographic position index (5km circle), topographic roughness index (5km circle), distance to coast and distance to one haul-out (Razende bol) as an example.

2.4.1.2 Sediment type

To describe sediment type in this study, we used % mud (*Figure 5*). Sediment data was obtained from a combination of two data sources. For the Dutch EEZ data, details can be found at http://www.emodnet-seabedhabitats.eu/pdf/Imares_Dutch_Marine_landscape_Map.pdf. For other areas in the North Sea, we used maps created by Helmholtz-Zentrum Geesthacht (HZG) as part of the NOAH project (https://www.noah-project.de/habitatatlas/substrate/index.php.de).

2.4.1.3 Bathymetry

Bathymetry data were extracted from the harmonized EMODnet Digital Terrain Model (DTM, see http://www.emodnet-hydrography.eu/), which is based on regional DTMs, and gaps with no data coverage were completed by integrating the GEBCO Digital Bathymetry (*Figure 5*)

2.4.1.4 Topographic position index

The topographic position index (TPI, function tpi, package spatialEco (Evans, 2020)) is defined as the height of each pixel relative to the average height of pixels within a prespecified radius. High TPI values characterize peaks and ridges, while low TPI values characterize gullies. Here TPI was calculated for a radius of 5 km, describing topographic features at similar spatial scale.

2.4.1.5 Distance to pile driving and the construction site

Different mechanisms may cause seals to avoid the wind farm construction area. In the behavioural response analysis (2.3), we investigated if seals changed descent speed at the onset of pile-driving of a single monopile, indicating a reaction to the event. In the habitat analysis we investigate of seals show a general avoidance of the wind parks during the construction and operational phase. The construction phase was defined as the period between the piling of the first and last monopile. Construction (piling) of Belgian parks commenced prior to the deployment of the GPS trackers on the seals, hence we could not differentiate between construction and operational phase in the Borssele parks. To capture avoidance behaviour, variation in seal density was modelled as a function of the log of distance to the nearest monopile of the constructed wind farm. We assumed no effects beyond 50 km, therefore, the effect of the wind farm at distances beyond 50 km was assumed to be equal to 50 km. In this analysis, we did not consider the effect of wind parks elsewhere in the North Sea, since we were solely interested in potential avoidance of the Borssele wind farm area.

2.4.2 Processing seal tracking data

First, records of unrealistically long haul-out durations with no subsequent trip to sea, assumed to be caused by tags falling off on land (mostly during the moult), were removed from the analysis. Because seals may behave different just after the tagging event, data from seals with less than 10 days of data were removed. To predict absolute densities at sea for the entire population based on aerial survey haul-out counts, it was necessary to model the spatial distribution of tracked seals relative to the haul-out sites from which they performed trips and, for this, each trip to sea was linked to the corresponding start and end haul-out as follows. The GPS data loggers record the start and end of each haul-out event (i.e., continuously dry for at least 600 s). The location of that haul-out event was estimated as the average location of all GPS-fixes during that haul-out event. If no location estimate was obtained during the actual haul-out event, the location closest in time before or after the haul-out event was used. For trips with different start and end haul-out site (transitory trips), all locations prior to the midpoint (in time) of the trip were allocated to the start haul-out, and those after the midpoint to the end haul-out.

In previous models, habitat models were fitted to data from all seasons and an interaction between distance to the haul-out site and season was included to capture seasonal changes in distribution. The grey seal and harbour seal deployments only took place in September, and for harbour seals tracking data were only available until February. Therefore, the habitat models for both grey and harbour seals were fitted to data from the winter months (September – February), and seasonal interaction were not included, which also reduced computation time. To further reduce computation time, the GPS tracking data were subsampled at 11-hour temporal resolution. This 11-hour period prevents bias in the sub-sampled distribution caused by daily or tidal cycles. The GPS data from the Borssele deployments in 2019-2020 were not sub-sampled.

2.4.3 Habitat analysis

The aim of this analysis was to estimate a function ($w(X_S)$) describing the density of seals as function of the environmental variables depicted in 2.4.1. We call this the Species-Habitat Association Model (SHAM). The SHAM can be fitted based on use-availability data by using the Conditional Inhomogeneous Poisson Process (CIPP) likelihood function

$$l_{CIPP}\left(\beta; X\right) = \sum_{m=1}^{M}\sum_{k=1}^{K_m}\left\{\log\left(w(X_k^U)\right) - \log\left(\int_{S\in A} w\left(X_S\right)dS\right)\right\} \quad 1.$$

Here, *M* is the total number of unique seals, and K_m is the total number of locations of the *m'*th seal. The integral represents what is available to each animal and is evaluated for each seal location and is conditional on the haul-out to which the *m'*th location belongs. This integral is approximated by sampling points from geographical space and evaluation $w\left(X_S\right)$ for those "availability points".

To approximate the integral of the likelihood, for each GPS location, 20 random points were selected, with sampling weights of 1/distance. For each sampled point, the total area represented by all nearest points (sampled and unsampled) was calculated and used as model likelihood weights. quadrature weights q_n. This will lead to an unbiased sampling design, but higher resolution near those places heavily used by seals.

The function $w(X_S)$ was modelled as the exponent of the linear predictor *η;* $w = e^{\eta}$
The simplest form of the linear predictor is to assume that it is a linear function of the environmental variables $x_1 - x_J$. However, animals often respond non-linearly to environmental variables, e.g., they might have a peak preference for a particular explanatory variable. This non-linearity was included in the model by including smooth functions of *x:*

$$\eta = \beta_0 + s(x_1)\cdots + s(x_j)\cdots + s(x_J) \quad 2.$$

Here, b-spline smoothers consist of five (for distance to haul-out) or four (for all other explanatory variables) basis functions, each being a different cubic polynomial of the original explanatory variable x_j (function bs() within the R library 'splines') (Ramsay and Silverman, 2005).

$$s(x_j) = \sum_{k=1}^{K} b_k f_k(x_j) \quad 3.$$

where f_k is the *k*th basis function. The wildlife telemetry locations come from different individuals that may differ in their preference for environmental conditions. To capture this hierarchical structure and the non-independence in the observations within an individual, mixed-effect models were fitted. Each parameter *b* in eq. 3 is treated as a normally distributed random variable (Pinheiro and Bates, 2000).

$$b_{j,m} = \beta_{j,0} + \nu_j \quad 4.$$

where *m* refers to the *m*th individual and ν_j are the random effects which are assumed to have a joint multivariate normal distribution with a mean of zero and a variance-covariance matrix Ψ, representing within-class variability (Pinheiro and Bates 2000). Defining the coefficients of the basis-functions of the b-spline smoothers as random effects, allows one to estimate if the functional form of this relationship differs between individuals.
In addition to the random effect, also a spatially autocorrelated error structure was included. For this, a spatial mesh is created based on all the model data (use and availability points) with a maximum edge length of 50km in the core area and 100km in the boundary area and a cut off of 5km (function i`nla.mesh.2d`). Based on the mesh, a Matern SPDE model, with spatial scale parameter *κ(u)* and variance rescaling parameter *τ(u)* is estimated (function `inla.spde2.matern`).

Models were fitted using the Template Model Builder package (TMB): an R package for fitting statistical latent variable models to data. The final model was used to make spatial predictions of seal density. By setting the variable "distance to wind farms under construction or in operation" to zero, the seal distribution with and without the presence of a wind farm can be estimated and shown.

2.5 Aerial surveys

In the Delta area, monthly surveys were conducted to count seals (Hoekstein *et al*., 2022). In the largest part of the area, seals were counted around low tide from an airplane flying at an altitude of ~150m. These aerial surveys covered all known haul-out sites, except the Grevelingen area which was surveyed by boat. In the latter area annotation of the location of sightings were logged differently than the aerial results resulting in seemingly more haul-out locations than expected (*Figure 6*).The data provided for this study contained numbers of grey and harbour seals and their pups identified at the various haul-out sites. Similar surveys have been carried out since the 1990's, though since November 2013, no surveys were done in September and October while in November only partial counts were conducted covering the coastal zone. For this study additional counts were commissioned for September in 2019 and 2020. In recent years, seal groups were photographed during the flights and seals were identified from the pictures.

2.5.1 Data processing

The survey data were used to investigate possible changes in abundance and distribution in relation to the construction activities.
Data provided included number of individuals per species (harbour or grey seal), survey date, region name, location name and code and spatial coordinate. The exact coordinates of hauled out seals could vary between surveys, as the seals could haul-out on different parts of the sandbank, depending on the tide-dependent availability of the sandbank. The survey counts were divided in 11 sub areas, taking account of natural barriers and distances between haul-out sites. These are shown in different colours in *Figure 6*.

The data provided did not include zero's, i.e., there was no record of haul-outs being visited, but without seals encountered. Therefore, we first grouped all haul-outs into 11 sub-areas. If a member of one species was observed (e.g., harbour seals), but the other species wasn't (e.g., grey seals), the count for the latter species was assumed to be 0. If no survey in a sub area was carried out in a specific month, this was mentioned in the rapports and the count was marked as *NA* (and not included in the analysis). In several cases more than one survey per month was carried out, often because flights were affected by weather, and repeated several days later. In those cases, the most complete survey was selected. This survey data processing resulted in a count for each sub-area and each year-month combination.

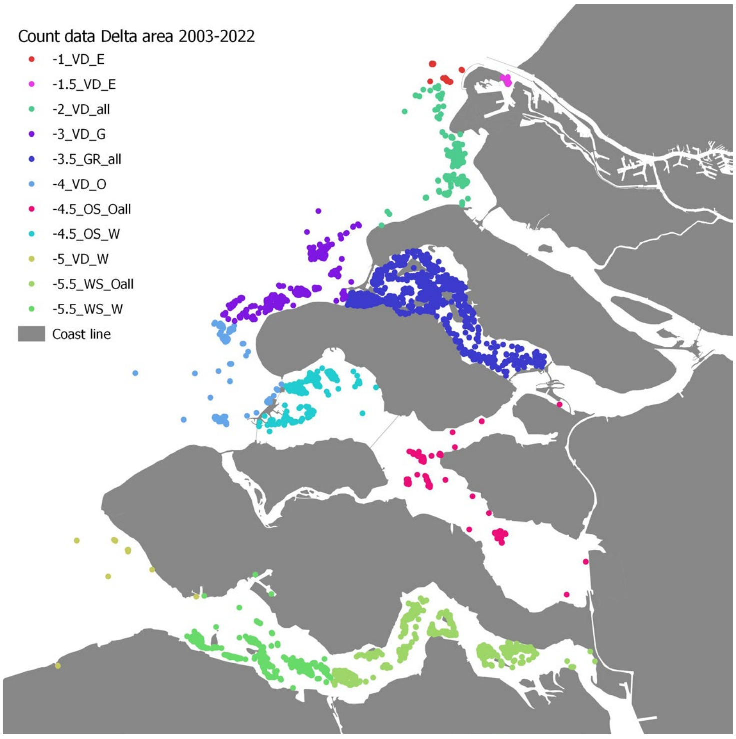


Figure 6. GPS location of the survey plane with seal sightings recorded during monitoring of 2003-2021 (data DMP). Different colours represent the different sub regions used in this report.

2.5.2 Analysis

GAM models were fitted to best describe the observed variations in counts prior to the onset of pile driving in the Borssele area (October 2019). We assumed seal numbers would be influenced by seasonality (i.e. month) following their specific phenology. In addition, as the seal population is recovering from earlier decrease, the counts could also show a changing annual trend. Furthermore, it was assumed that at a sub area level local circumstances, including human activities or natural causes (for example, if the haul-out site was used for breeding or not) would affect the number of seals seen in an area. We assumed for the model a negative binominal distribution and included a smoother for both the effect of year and month, which was allowed to vary between sub-regions. The two species were tested separately.

The full model fitted, assumed the seal counts to vary between months and years as a smooth function (s()), and this smooth was allowed to vary between sub regions. This was achieved by using a factor smooth interaction (smoothing basis bs = ‘fs’). To prevent overly complex smooths, k was set to a maximum of 5.

counts ~ s(year ,sub region, bs="fs", k=5)+s(month ,sub region, bs="fs", k=5)

This model was fitted to all count data but excluding data from October 2019 onwards (when the construction of Borssele 1-4 started). Next, this model was used to predict the expected number of seals in each month and sub region, and these predictions were used as a baseline to compare against to observed counts. When the model predictions are different from the observed counts, this could indicate a behavioural change.
All analysis was done using R version 4.1.0.

2.6 Stranding data

Data was directly provided by *Waarneming.nl*. Waarneming.nl is a public database on which all wildlife observations can be placed by any member of the public. Data is authenticated by a validator before being published, though control of a report is not always possible as it is an observation in the field, often made by laypersons. For many of the stranded animals, the seal rescue centres Ecomare and Pieterburen (including data from A-Seal) have uploaded their observations of all seals to the database, going back to the 1970's. For the Delta region, most data were provided by Jaap van der Hiele. Together with the observations from other volunteers and the more recent stranding services reporting on waarneming.nl, a database of seal strandings is now available.

For this study, only the dead animals were extracted from the database. Data included coordinate, often species, date, sex and size were given and occasionally extra details in the comments. When possible, data found in the comments were used to complete the age categories. For example, when in the comment length =1m was mentioned, the seal was notably a young animal and the column "age" was updated accordingly. In total over 9000 records (1984-2022) of seal strandings (dead) were retained, 2332 of which in the Delta area. Details are presented in Table 6.

Table 6. number of dead seals reported in the Delta area 1984-2022

SEX	AGE GROUP	*grey seals*	*harbour seals*	Pinnipedia spec.
Male	Adult	182	151	1
	Subadult.	60	120	1
	Young	40	140	1
	Unkn.	40	62	
		322	**463**	**3**
Female	Adult	48	102	
	Subadult.	34	97	1
	Young	17	33	
	Unkn.	34	40	
		133	**272**	**1**
Unkn.	Adult	126	147	3
	Subadult.	47	169	3
	Young	96	197	7
	Unkn.	97	247	17
		580	**1099**	**30**
Total		**803**	**1495**	**34**

Given the potentially incomplete data and lack of information on other activities in the area we chose to describe the observations, rather than trying to explain the possible effects of pile driving as a separate driver for the observed mortality.

3 Results

3.1 Seals tracked

Ten seals of both species were captured and deployed with a tracker. Length and weight of these animals were compared to other seals captured in the past 30 years, keeping account of the seals phenology as this would affect their weight. During the capture in autumn, grey seals are expected to be relatively heavy in autumn as they almost recovered from their weight loss during breeding and moulting in December and April respectively. In contrast, harbour seals breed and moult in June/July and August, respectively. Hence, during the capture event, they have not recovered from the weight loss and are expected to be relatively light for their length. The studied seals were therefore only compared to seals captured in Autumn.

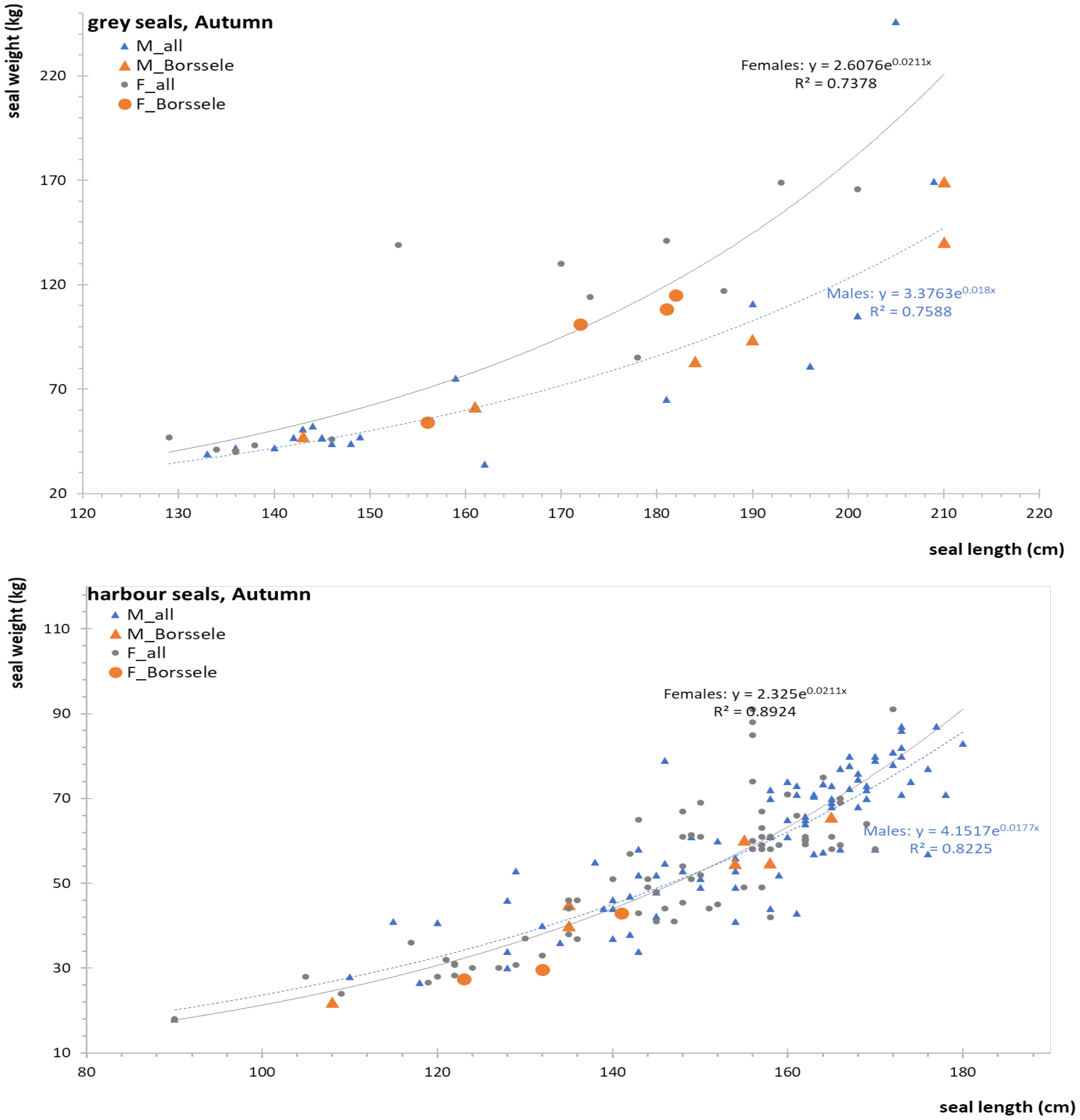


Figure 7. Length and weight of seals captured in September 2019, compared to all seals captured in autumn 1990-2017. Top grey seals, bottom harbour seals. Orange markers indicate tracked animals. An exponential function was used to capture the (non-linear) relationship between seal length and weight.

Compared to an exponential relationship of length and weight based on all seals weighed (see *Figure 7*), the tracked grey seals were in average 5% lighter than the weight of the animals captured in previous years, but this effect was not significant (p=0.36, GLM with Gamma distribution and log-link) The harbour seals tracked for the Borssele project were on average 15% lighter compared to those tracked in previous years. This effect was not significant (p=0.1), but given the very small sample size of only 10 individuals, this p-value is quite low, and at least indicative of an effect. In both cases, females were more different than males, this again is more apparent in the harbour seals.

3.2 General movement of tracked seals

3.2.1 Grey seals

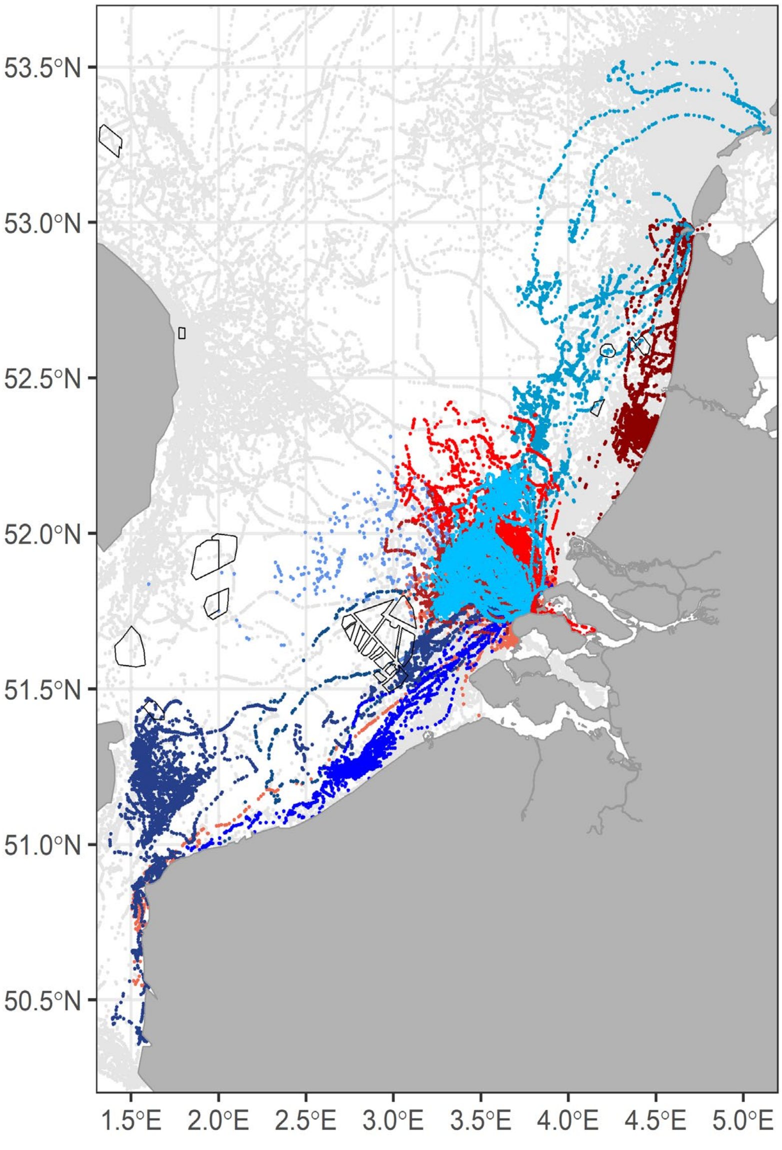
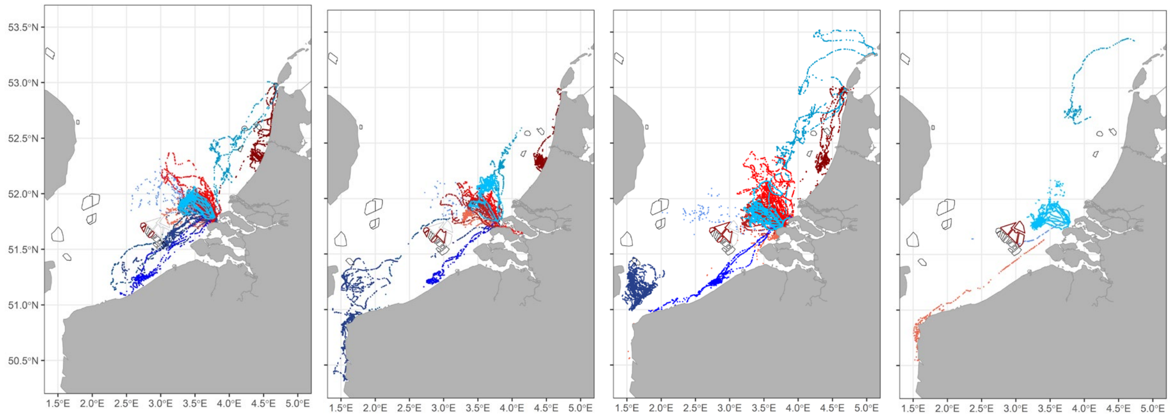


Figure 8. Movements of 10 tracked grey seals sept 2019-mar 2020. Red tones: females; blue tones: males; light grey: tracks of previous projects

The distribution of the ten tracked grey seals ranged from off Vlieland to the north to the Baie de Somme in the south. One individual spent time in the west near the English coast (Figure 8). Occasionally a female grey seal entered the Grevelingen and another female entered the Westerschelde. During this whole tracking period, pile driving in the four different parks was carried out, overlapping in time. Figure 9 depicts the movements of grey seals during these four different periods of pile driving. During the first two periods all trackers were functioning, while in the course of the third period four trackers were lost, and by March 14th 2020, no data were received from any of the devices.



8 Sept.-19 Oct. 2019	**20 Oct.-13 Nov 2019**	**14 Nov 2019-1 Jan. 2020**	**1 Jan.-20 Apr. 2020**
Seamade & Northwester pile driving	*Seamade, Northwester, & Borssele 3&4 pile driving*	*Northwester, & Borssele 3&4 pile driving*	*Borssele 3&4 & Borssele 1&2 pile driving*

Figure 9. Movements of 10 tracked grey seals sept 2019-mar 2020. In the course of different pile driving regimes. Active construction sites indicated in red. Tracks: red tones: females; blue tones: males.

3.2.2 Harbour seals

The ten individual harbour seals that were tracked ranged less than the grey seals: from off Ijmuiden in the north to the Belgian coast in the south. Two individual males entered the Westerschelde, one the Grevelingen. The females’ range seemed more restricted than the males’ as they stayed in the vicinity of the area where they were caught (Figure 10). Like the grey seals during this period, they experienced pile driving in the four different parks. The movements of harbour seals during these four different periods of pile driving are depicted in Figure 11.

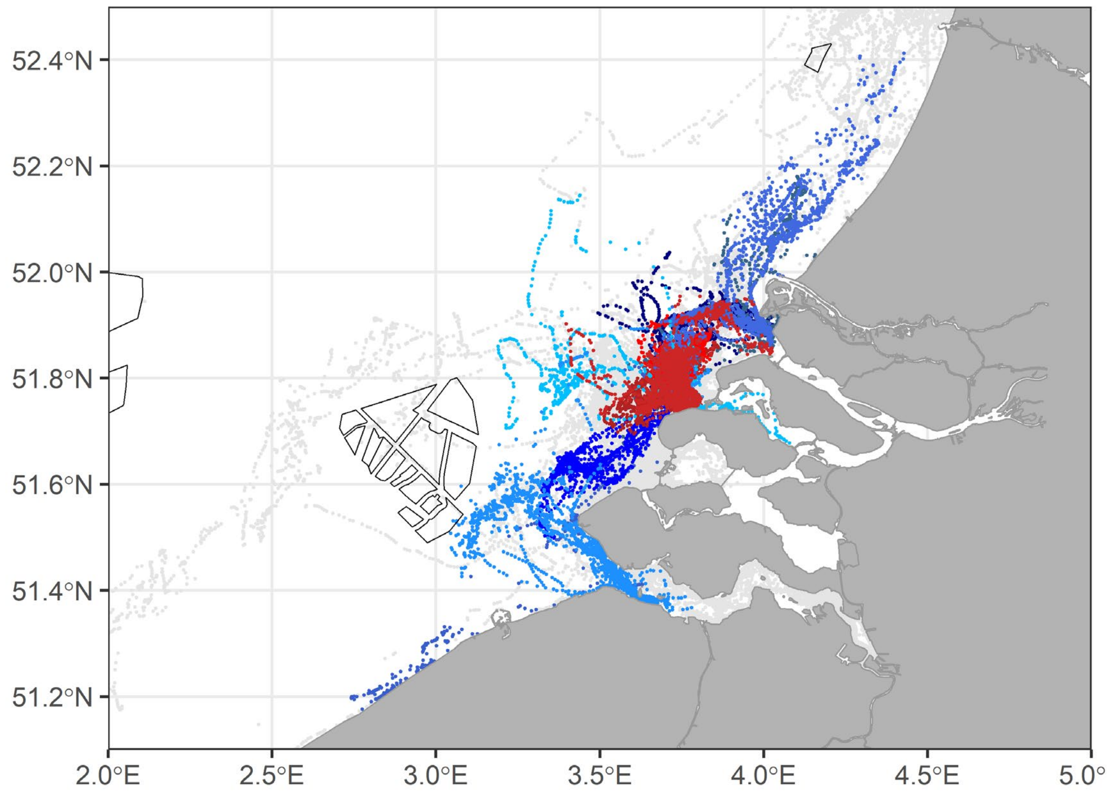
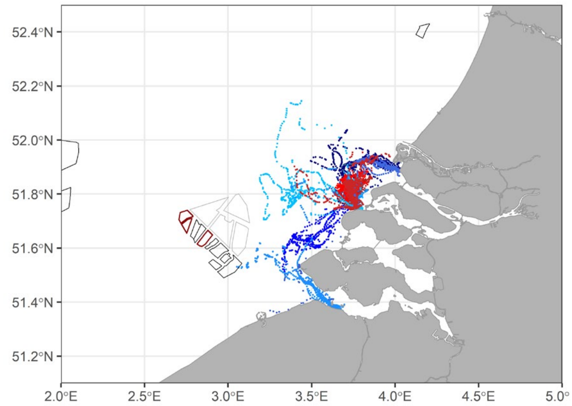
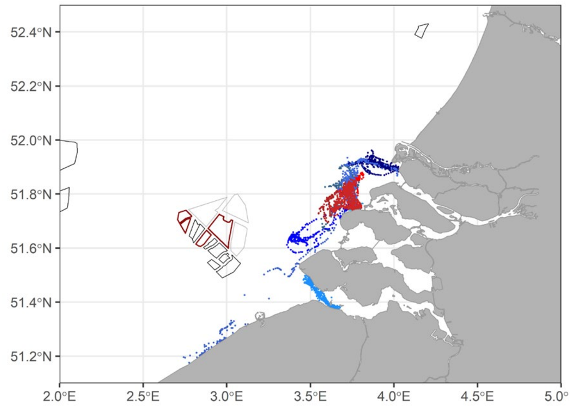


Figure 10. Movements of 10 tracked harbour seals sept 2019-mar 2020. Red tones: females; blue tones: males; light grey: tracks of previous projects

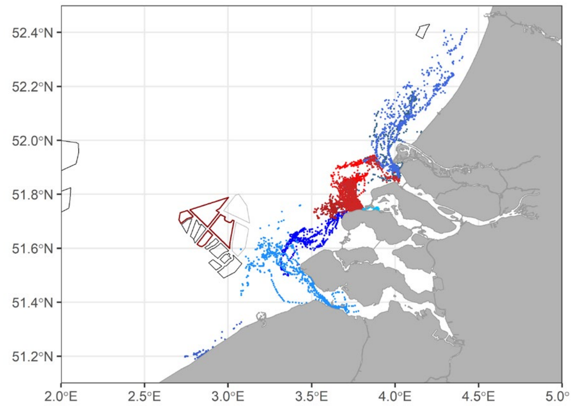
During the first period all trackers were functioning, however, in the course of the second period one tracker was lost and three others during the third period. During the fourth period all other six stopped functioning by February 8th 2022.



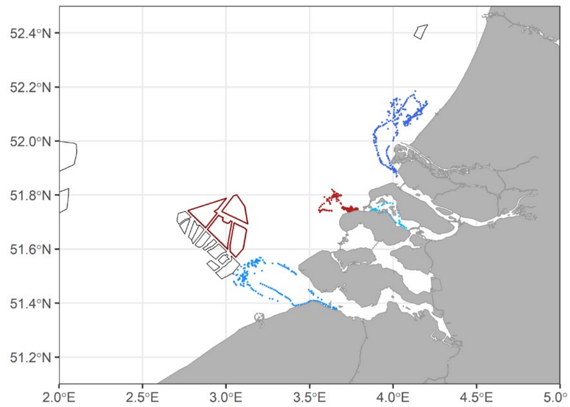
8 Sept.-19 Oct. 2019 *SeaMade & Northwester pile driving*



20 Oct.-13 Nov 2019 *SeaMade, Northwester, & Borssele 3&4 pile driving*



14 Nov 2019-1 Jan. 2020 *Northwester, & Borssele 3&4 pile driving*



1 Jan.-20 Apr. 2020 *Borssele 3&4 & Borssele 1&2 pile driving*

Figure 11. Movements of 10 tracked harbour seals sept 2019-mar 2020. Active construction sites indicated in red. Tracks: red tones: females; blue tones: males.

After period 1, the harbour seals seem to stay more coastal than earlier, also than seals in previous tracking projects.

3.3 Behaviour in relation to pile driving

In this study we investigated how the seal's diving behaviour changed during active pile driving and how this change depends on the distance to the construction site. Despite the relative proximity of the Borssele construction site, very few seals were found to be close to Borssele during pile driving. For example, no seal was within 5 km, only one seal was within 10 and in only 3 occasions a seal was within 15km (*Figure 10*). One note of caution: These distances were estimated for each dive-record and based on interpolation between successive GPS locations. In some instances, the time between GPS locations could be several hours and this could lead to an imprecise location estimate.

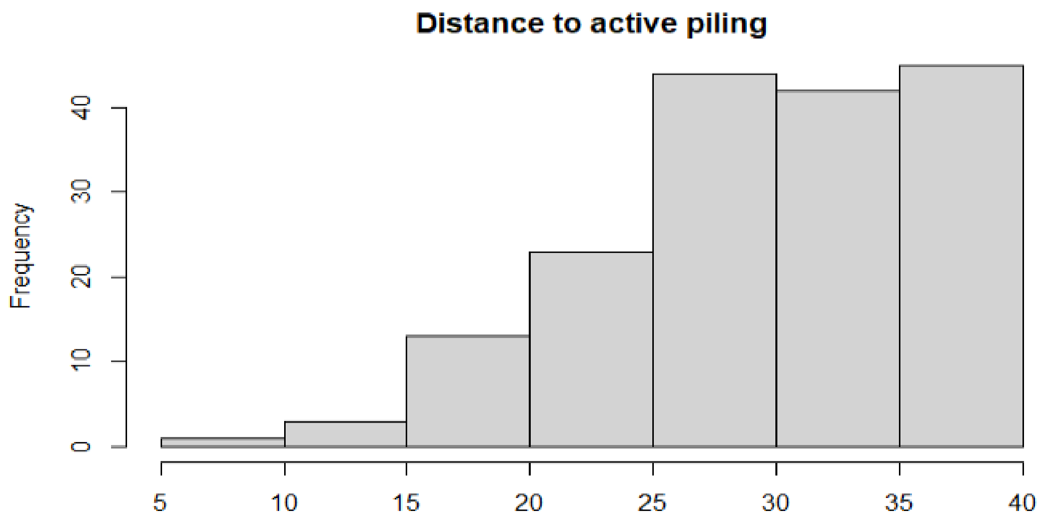


Figure 12. Frequency distribution of the number of events where GPS tracked seals were within a specific distance (in km) to a pile driving event

For each exposure (i.e., at the onset of pile driving, the seal was within 35 km), we calculated the change in descent speed between the period before and after the commencement of pile driving. A previous study showed that (grey) seals exposed to nearby pile driving, revealed a significant decline in vertical speed (*Figure 13*).

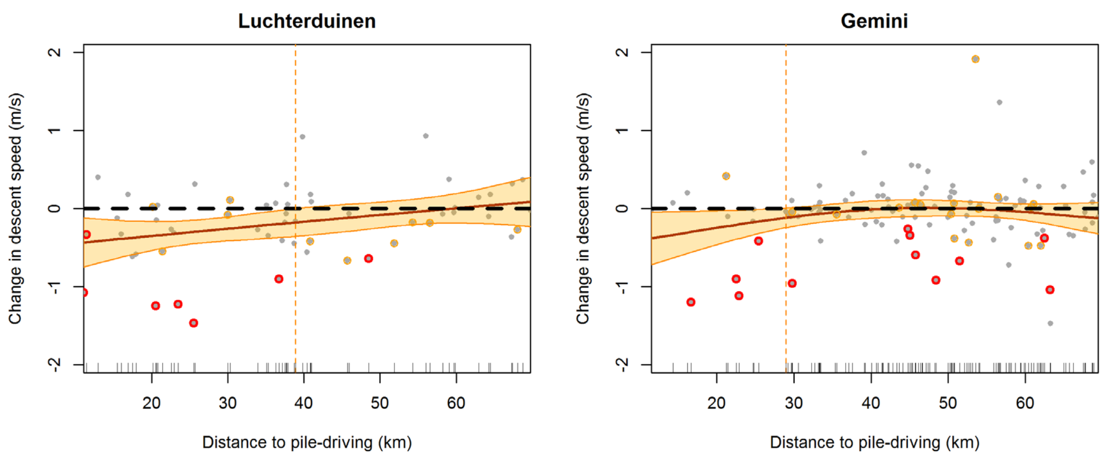


Figure 13. Change in descent speed (m/s) during pile driving for Luchterduinen (left) and Gemini (right), as function of distance to the pile driving. Each grey point represents an exposure. The solid red line represents the mean estimate, and the shaded orange area the 95% confidence interval (with 2.5% and 97.5% lower and upper limits, respectively). The orange vertical line indicates 97.5% certainty of a significant decrease in descent speed. Thick red circles are exposures where the descent speed of individual animals dropped statistically significant during piling. The lighter orange circles are exposures where significant changes in other behavioural response variables were observed (i.e., average dive depth or change in (horizontal) movement).

The underlying hypothesis is that when seals are foraging, they are expected to have a relatively high (vertical) descent speed, since they are more likely to dive straight down towards the bottom. When exposed to pile driving, we expect seals to switch to a travelling speed, with more diagonal dive movement, and hence smaller vertical descent speed. Figure 14 shows the change in descent speed as function of distance the Borssele 1, 2, 3 & 4, Sea Made and North Western construction site.

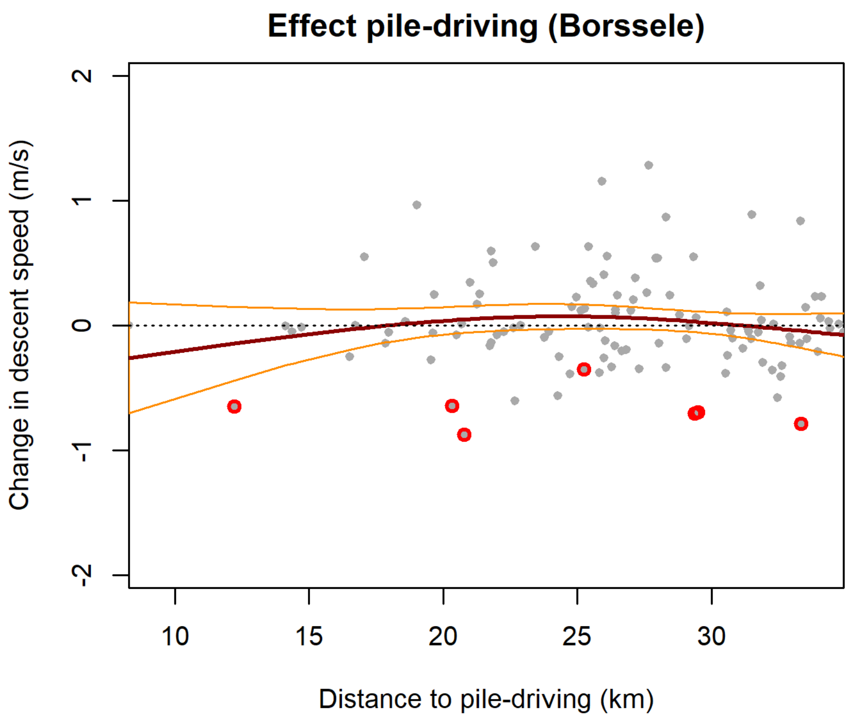


Figure 14. Change in descent speed (m/s) during pile driving for Borssele as function of distance to the pile driving. See Figure 13 for more details

On average, the exposed seals, revealed a decline in descent speed at closer distances, however this was not significant, most likely due to limited data availability. Behavioural responses are most likely for individuals exposed to pile-driving at short-range, and therefore these exposures will be inspected in more detail.

The closest exposure was for a harbour seal (pv69-138-19) on 2019-12-26 at 8.3 km from the Borssele 3&4 construction site. Only one GPS location fix was obtained during the pile driving, with no GPS fixes several hours before pile driving. It is not unlikely that the seal was even closer to the construction site prior to pile driving. Approximately five hours prior to pile driving, the vertical descent speed was approximately 0.75 m/s but declined in the subsequent hours. During the pile driving, the average descent speed was 0.5 m/s. Two hours prior to pile driving, the seals' diving profiles reveal an erratic pattern with short dives and shallow dives, with longer surface periods in-between. Such an erratic diving pattern was often observed for seals exposed to pile driving at close distances and does suggest that the seal responded to activities related to pile driving (e.g., preparation of the pile driving vessel). No decline in descent speed was observed at the onset of pile driving, but descent speed was already low prior to pile driving. Given the close proximity of the construction site, it is not unlikely that the seal already detected the ongoing construction and responded prior to pile driving, but also other unregistered events, like passing ships could have initiated the behavioural response.

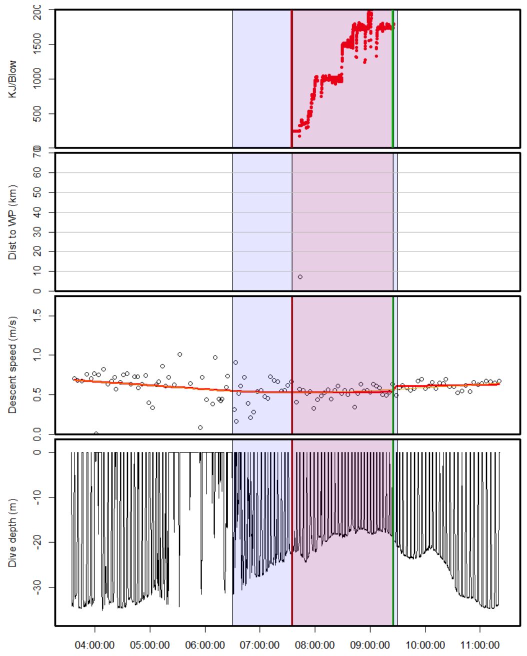


Figure 15. The diving behaviour prior, during and after pile driving for harbour seal pv69-138-19, 8.3 km from the construction site on 2019-12-26. The top panel shows the blow intensity (y-axis, in kJ) as function of time (x-axis). The blue transparent area is the period when the ADD was turned on. The red transparent area represents the construction period as defined in the summary table. The 2nd panel shows the distance to the construction site (in km). Note, only one GPS location fix was obtained during the entire period shown. The 3rd panel shows the average descent speed between 1.5m below the surface and 80% of the maximum dive depth of each dive. The red line shows the model-based estimate, used to estimate changes in descent speed between the different periods. The bottom panel shows the dive profile.

The 2nd closest exposure was for a grey seal (hg69-158-19) on 2019-12-16/2019-12-17 at 12.2 km from the Seamade construction site (Figure 16). Note however, that no GPS location estimate was obtained in the period around the pile driving, and hence, the estimated (interpolated) location of the seal during the pile driving is highly uncertain. There was no evident change in diving behaviour when the ADD was switched on, but this seal revealed a strong drop in descent speed just before the start of pile driving, slowly increasing during the pile driving. Approximately 30 minutes after pile driving had ceased, the descent speed returned back to pre-piling levels

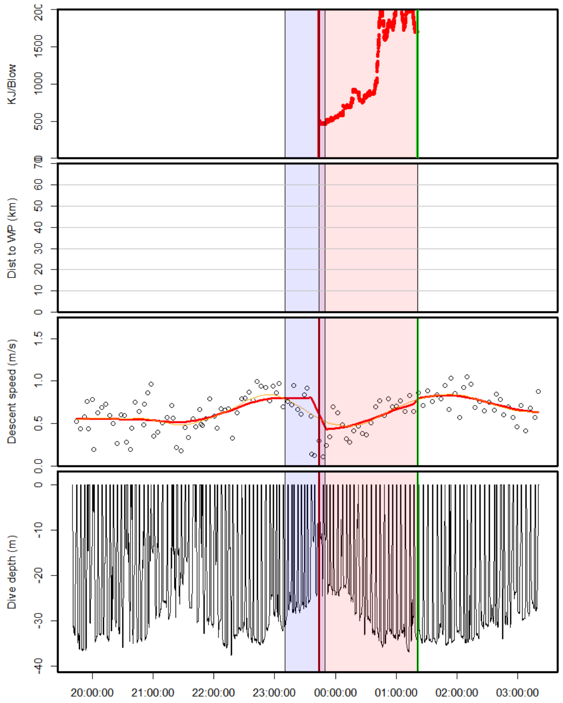


Figure 16 The diving behaviour prior, during and after pile driving for grey seal hg69-158-19, 12.2 km from the construction site on the night from 16 to 17 December 2019

The next three exposures were all at approximately 14km distance. The behavior of grey seal hg69-159-19 during one such exposure is shown in *Figure 17*.That seal that did not show a sudden change in descent speed after pile driving started (hence no significant change in *Figure 17*), but the descent speed did gradually decline during the construction period. The seal also changed its course during the construction period and increased swim speed towards its haul-out site, which suggests an avoidance and termination of its trip.

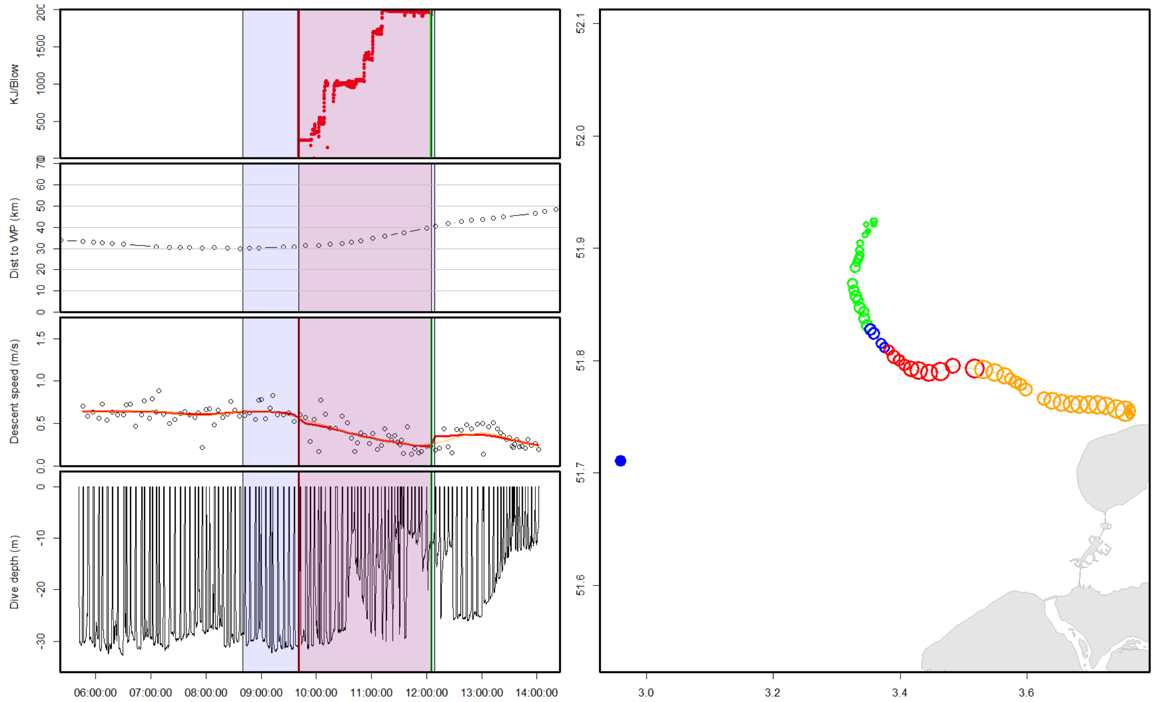


Figure 17 The behaviour for grey seal hg69-158-19, 31 km from the construction site on 25 December 2019. The right panel shows the movement of the seal during four different periods, namely the period prior to ADD and pile driving (green), during ADD (blue), during pile driving (red) and after pile driving (orange). The size of the circle indicates swim speed.

Many exposure events at larger distances did not reveal a clear change in behavior, one such an example is shown in *Figure 17*. However, there are also occasions where seals did change their behavior as soon as pile driving started. One such an event is shown in *Figure 19*. Although the bubble curtain is expected to attenuate the pile driving sound, this mitigation measure may not always be completely effective, potentially leading to behavioral changes beyond the expected impact distance (assuming effective mitigation).

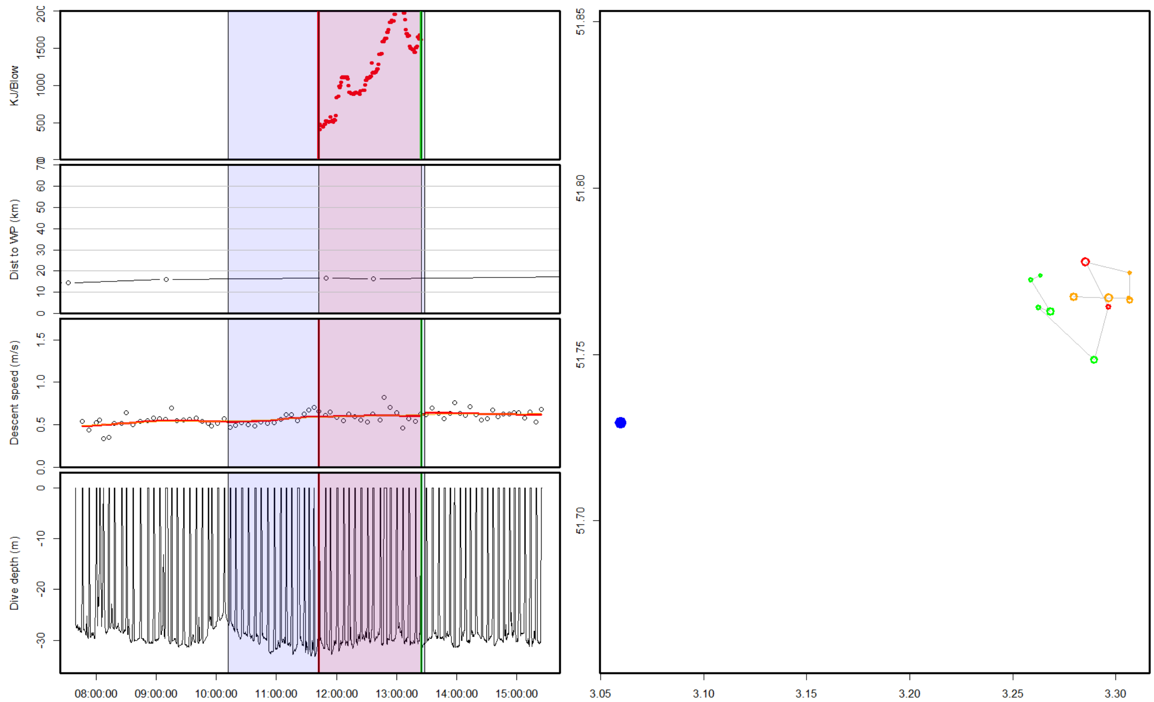


Figure 18 The behaviour of grey seal hg69-159-19, 15 km from the construction site on 8 January 2020. No clear change in diving behaviour or movement is apparent. However, descent speed is already reasonably low prior to pile driving, and the seal might already be in transit mode prior to pile driving.

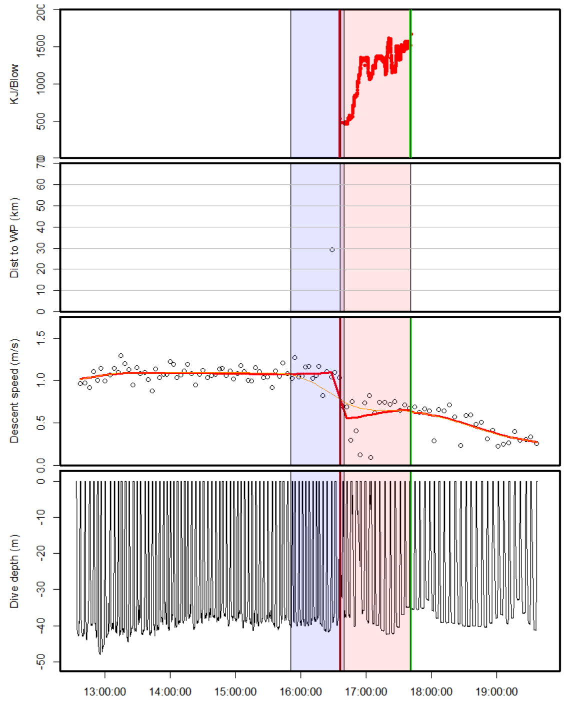


Figure 19 The behaviour for grey seal hg69-158-19, 29.4 km from the construction site (P81) on 28 November 2019. That seal is residing in relative deep water (40m) and showing a high vertical descent speed (>1 m/s) prior to pile driving. Immediately after the commencement of pile driving, a sudden drop in descent speed is apparent.

3.4 Behavioural response in relation to SEL

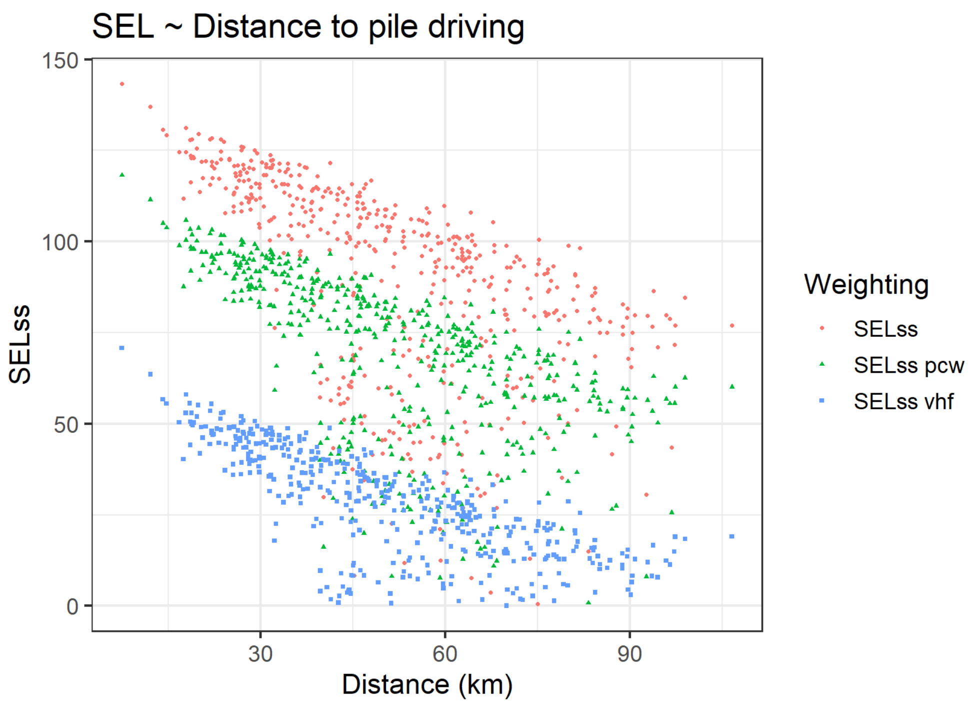
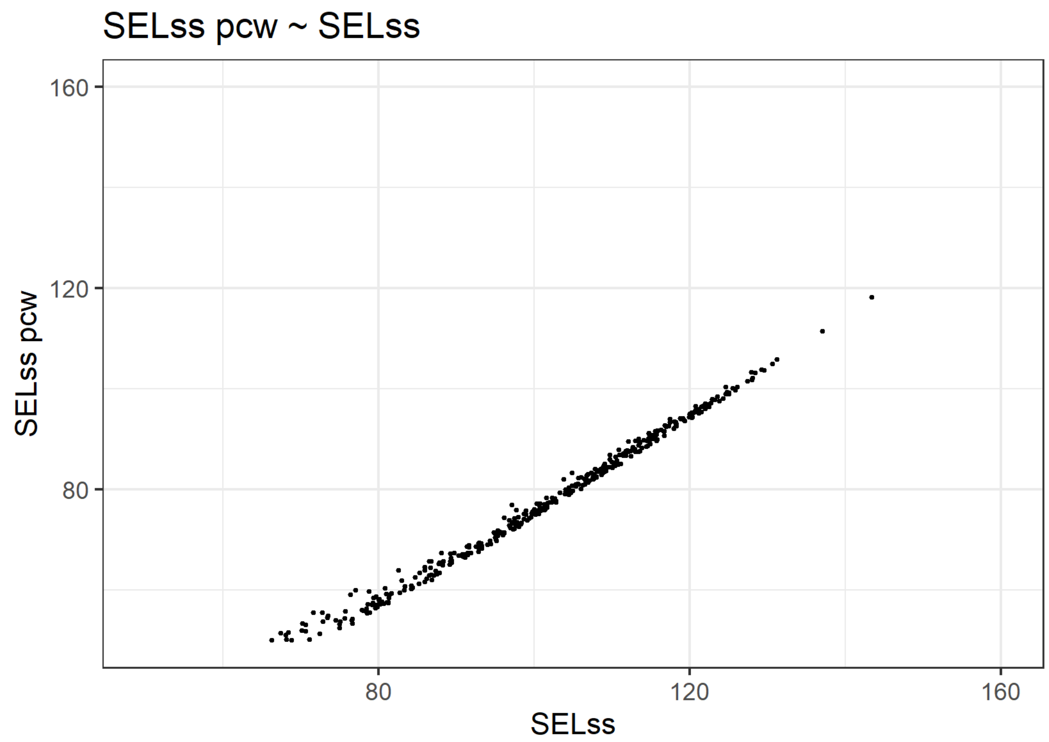


Figure 20. For all seal exposure events, the correlation between distance to the pile driving and Unweighted broadband single strike sound exposure level (SELss), broadband single strike sound exposure level (dB re 1 μPa^{2}s) and weighted for phocid carnivores in water (SELss pcw). For comparison also broadband single strike sound exposure level, weighted for very high frequency cetaceans (SEL vhf) is shown.

SELs are highly correlated with distance, however spatially-varying environmental variables also influence sound propagation. For example, Aquarius 4.0 also takes the effect of bottom geometry on sound attenuation into account (Figure 4). *Figure 20* shows the relationship between distance to the source and SELss for the seal exposure events. Distance to the pile-driving site is determined for the exposure events. The figure is based on the SELss estimates which assumes no effect of wind on attenuation (i.e. wind speed = 0 m/s).



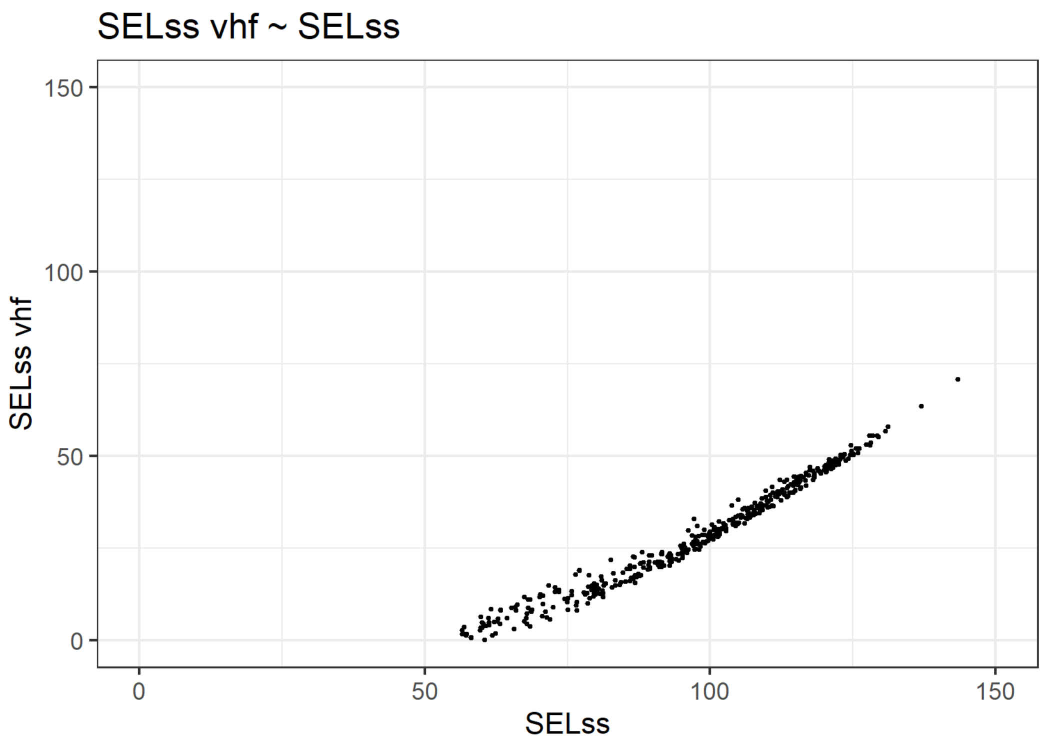


Figure 21. Relationship between unweighted broadband Sound Exposure Level single strike (SELss, in dB re 1 µPa^{2}s) near the bottom, and broadband SELss weighted for phocid carnivores in water (pcw, top figure) and broadband SELss weighted for very high frequency cetaceans (vhf, bottom figure)

The unweighted SELss and weighted SELss (pcw and vhf) are highly correlated, with SELss pcw being approximately 22 dB lower and SELss vhf being approximately 67 dB lower (*Figure 21*).

Next, for each individual exposure, the observed change in descent speed was linked to estimated perceived SEL. The study by Aarts *et al*. (2019) revealed that (grey) seals showed a decline in vertical descent speed as function of SEL. Note that these SEL estimates were based on Aquarius 1 and might not be directly comparable to SEL estimates generated in this study.

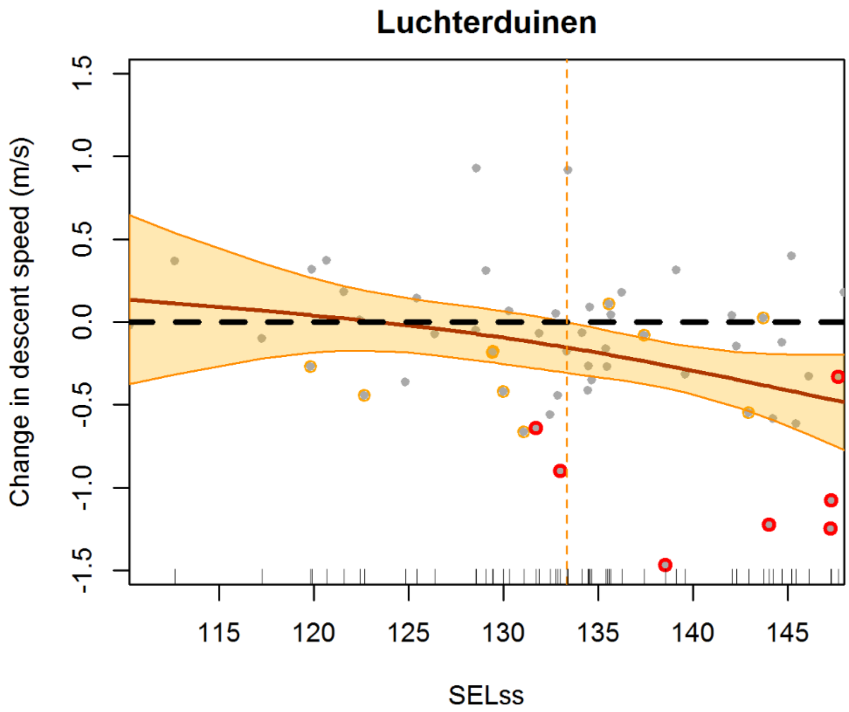


Figure 22. Unweighted Sound Exposure Level from a single strike (SELss, in dB re 1 μPa²s) during pile-driving and change in descent speed during the construction of Luchterduinen wind Park. SELss estimates assumed no effect of wind (i.e. wind speed of 0 m/s). The solid red line represents the mean estimate, and the shaded orange area the 95% confidence interval (with 2.5% and 97.5% lower and upper limits, respectively). Thick red circles are exposures where the descent speed drops significantly during piling. The lighter orange circles are exposures where significant changes in other behavioural response variables were observed (i.e. average dive depth or change in (horizontal) movement). The orange vertical line (at 133 dB re 1 μPa²s) indicates 97.5% certainty of a significant decrease in descent speed. For SELss exceeding ~137 dB re 1 μPa²s, the majority of exposures (10 out of 18) showed a significant behavioural response in one of the dive or movement variables.

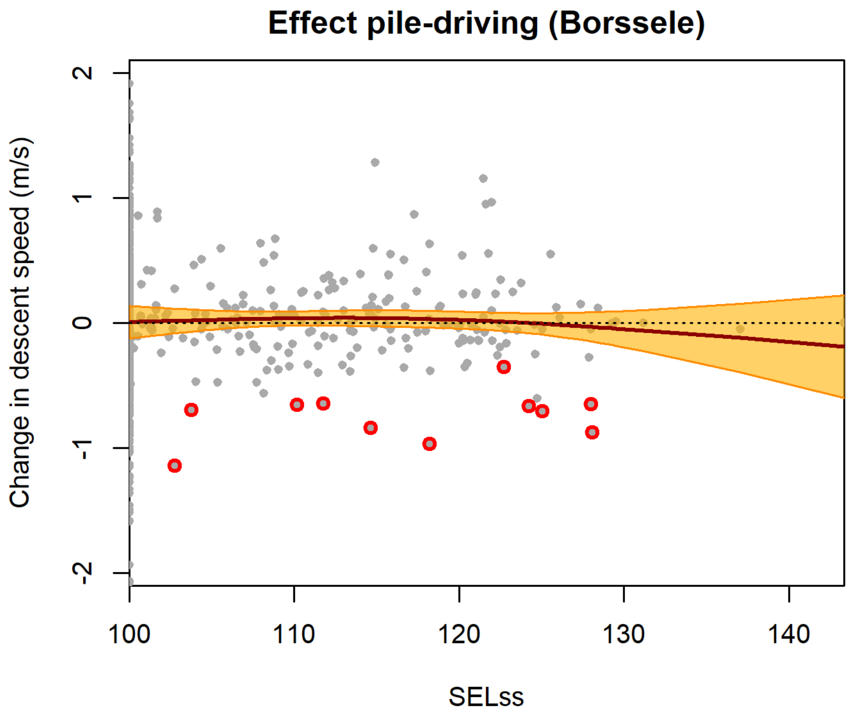
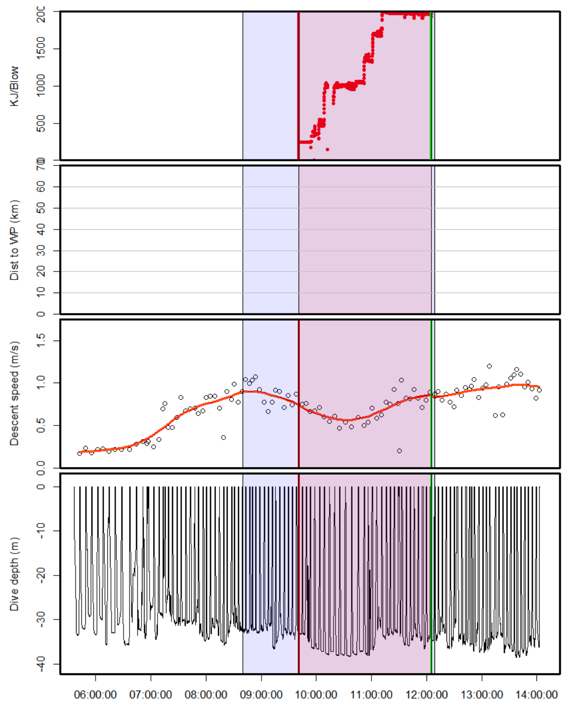


Figure 23. Change in descent speed in relation to unweighted Sound Exposure Level from a single strike (SELss, in dB re 1 μPa²s) during pile-driving in the different wind farms in the Borssele area. See details in Figure 22.

Note in Figure 23 the lack of points for SELss higher than 130 dB re 1 μPa²s. This resulted in too few points to find a significant relationship between the SELss and changes in descent speed, for the available exposure events.



3.5 Surveys

3.5.1 Grey seals

When comparing the counts between sub areas, it is clear that the Voordelta west of the Grevelingen (sub area -3_VD_G ; see *Figure 6* for locations) was used by the majority of grey seals. Observed numbers in this region exceeded 2500 animals in spring of 2021, while maximum numbers in other areas rarely exceeded 50 animals (*Figure 24*).

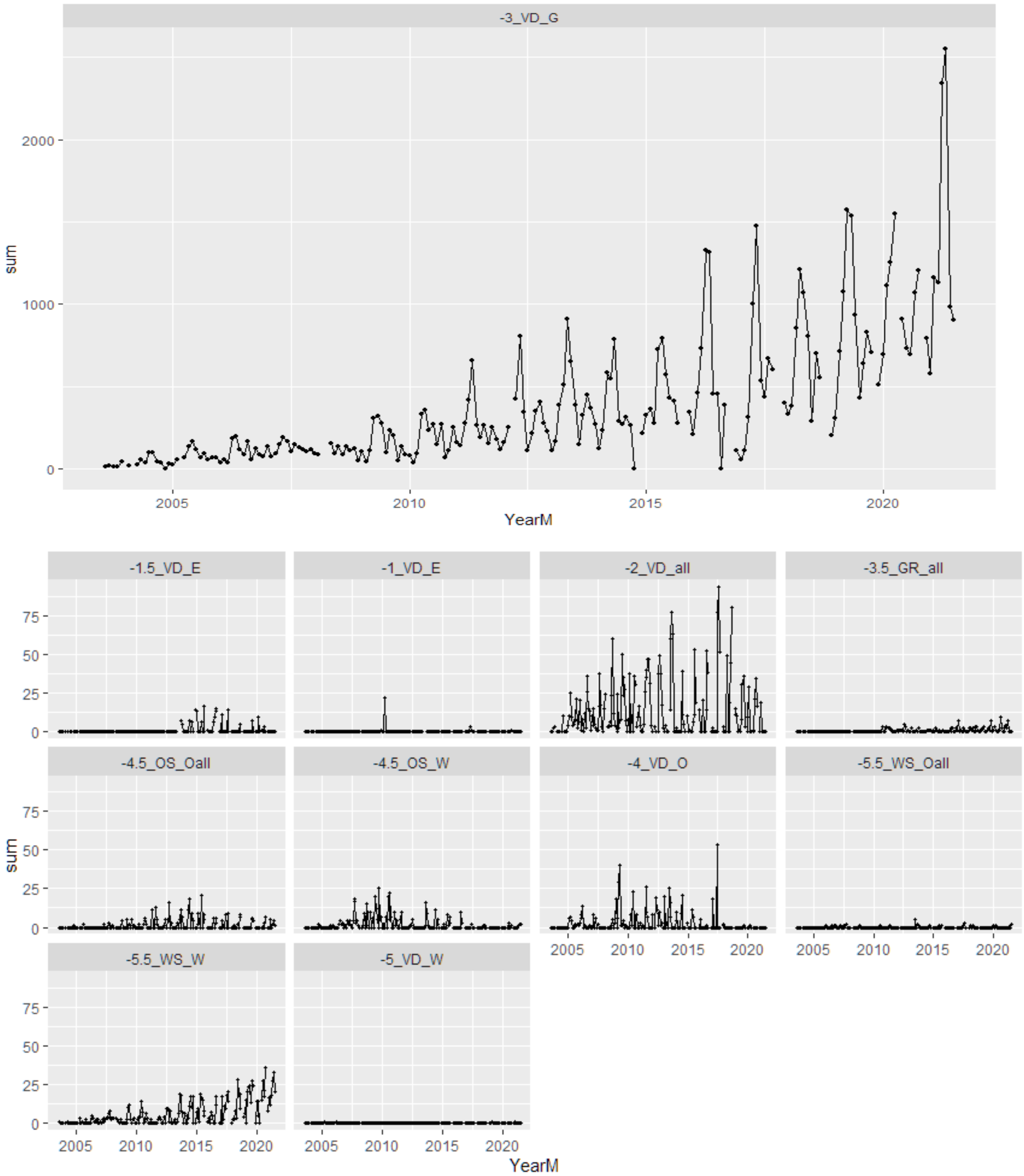


Figure 24. Count results for grey seals in the different sub areas of the Delta, see Figure 6 for locations. Note the different scale of sub area -3_VD_G.

Table 7. Results for the model describing the counts of grey seals in the different sub areas in relation to the year and month of the surveys

```
Family: Negative Binomial(0.546)
Link function: log

Formula: number of seals ~ s(year, sub area, bs = "fs", k = 5) + s(month, sub area,
    bs = "fs", k = 5)

Parametric coefficients:
             Estimate   Std. Error     z value    Pr(>|z|)
(Intercept)    2.442      1.239       1.972     0.0486 *

Approximate significance of smooth terms:
                          edf       Ref.df  Chi.sq      p-value
s(year, sub area)       36.37     54       346.8     <2e-16 ***
s(month, sub area)   26.22     54       200.1     <2e-16 ***

R-sq.(adj) =  0.838   Deviance explained = 82.7%
-REML = 3425.2  Scale est. = 1         n = 1921

Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

By plotting these model results (the modelling was done excluding data after October 2019) against all the counts we can discern if and when counts divert from the predicted values. This was not done for the sub areas in the Voordelta west of the Westerschelde (-5_VD_W), all haul-out sites east of the Westerschelde (-5.5_WS_Oall), and the areas west and north of the Haringvliet (-1_VD_E and -1.5_VD_E) as there were too few seals, i.e. less than 30 observations.

Results differed between the sub areas. In the Voordelta, particularly in the area west of the Grevelingen (-3_VD_G), more grey seals were seen in recent years than expected based on the model (fitted to data from earlier years). In contrast, this was not the case for the area west of the Haringvliet, or the Oosterschelde, where numbers seem to drop, though for the latter this seems to have been ongoing since about 2012. For the sub area in Oosterschelde (-4.5_OS_W) numbers are low and a similar drop occurs, though the numbers counted often exceed the prediction. Inside the Westerschelde (-5.5_WS_W), numbers after the Borssele pile driving commenced are often higher than predicted, though also here numbers are low (*Figure 25*).

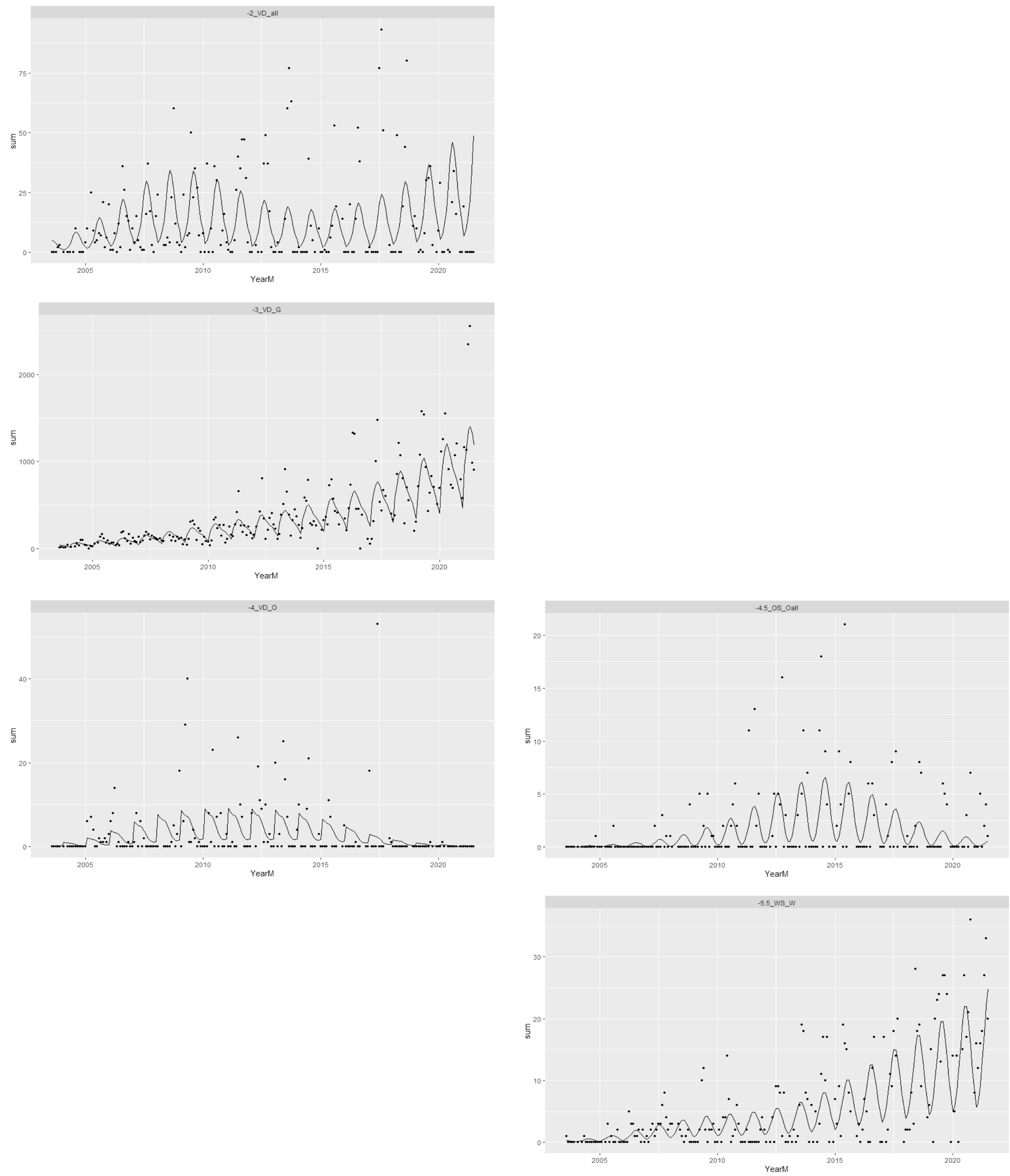


Figure 25. Predicted counts (line) and actual survey results (dots) for grey seals in different sub areas of the Delta. Locations are arranged from north to south, left column represent sub areas in the Voordelta, right column sites in land (-4.5 is the Oosterschelde, -5.5 the Westerschelde).

3.5.2 Harbour seals

Compared to the grey seals, harbour seals are more distributed throughout the different sub areas in the Delta (Figure 26; see *Figure 6* for locations), though in two areas numbers are very low, i.e. in the Voordelta, just south of Rotterdam (-1_VD_E) and In the Voordelta west of the Westerschelde (-5_VD_W).

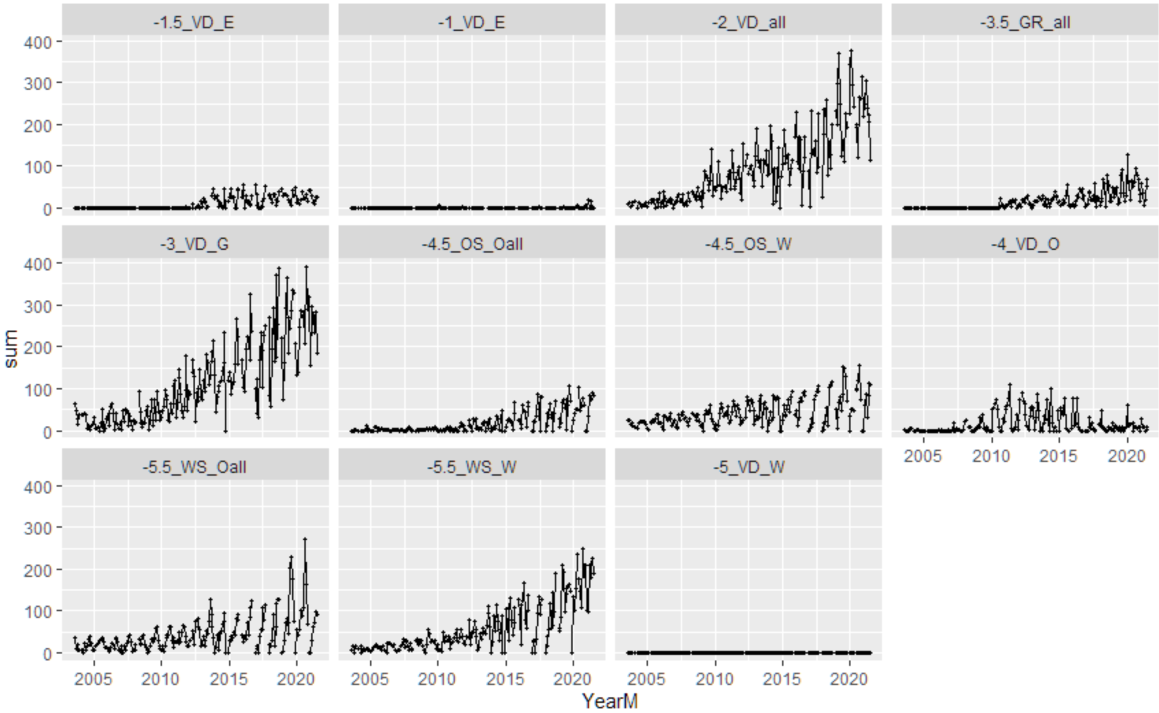


Figure 26. Count results for harbour seals in the different sub areas of the Delta, see Figure 6 *for locations.*

Table 8. Results for the model describing the counts of harbour seals in the different sub areas in relation to the year and month of the surveys

```
Family: Negative Binomial(0.546)
Link function: log

Formula: number of seals ~ s(year, sub area, bs = "fs", k = 5) + s(month, sub
area,
    bs = "fs", k = 5)

Parametric coefficients:
             Estimate  Std. Error   z value   Pr(>|z|)
(Intercept)   1.6923     0.9281    1.823      0.0682

Approximate significance of smooth terms:
                         edf     Ref.df  Chi.sq     p-value
s(year, sub area)      44.857 54.000 3104.06  <2e-16 ***
s(month, sub area)   3.184  3.645   53.94  <2e-16 ***

R-sq.(adj) =  0.779   Deviance explained = 82.7%
-REML = 6057.6  Scale est. = 1        n = 1925

Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

By plotting these model results (the model was fitted to data excluding observations after October 2019) against all the counts we can discern if and when counts divert from the predicted values. This was not done for the sub areas -5_VD_W (the Voordelta west of the Westerschelde) and -1_VD_E., (the Voordelta west of the Haring Vliet) as there were too few seals (i.e., less than 30 observations).

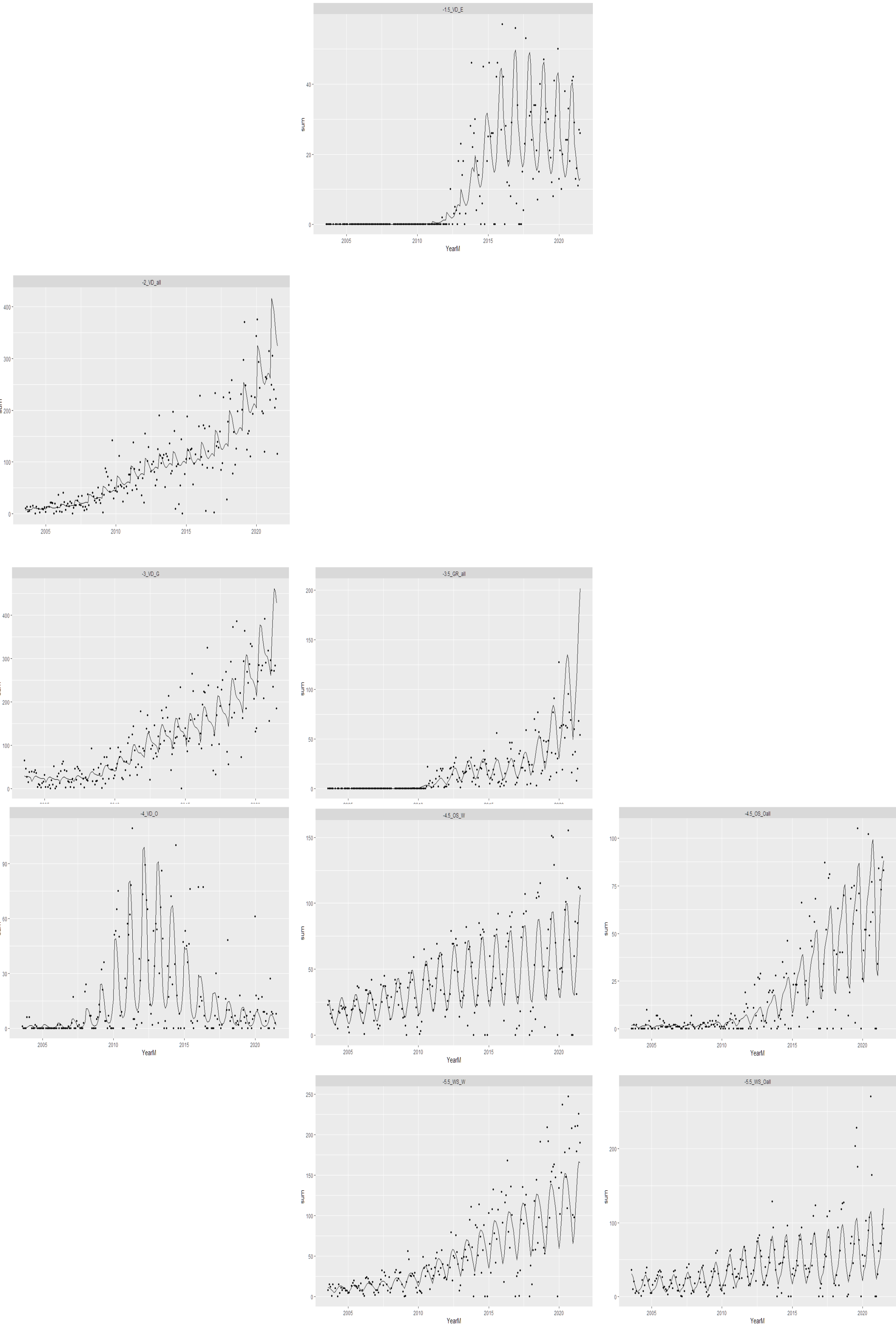


Figure 27. Predicted counts (line) and actual survey results (dots) for harbour seals in different sub areas of the Delta. Locations are arranged from north to south, left column represent sub areas in the Voordelta, right column sites in land (-1.5 is near Rotterdam Harbour, -3.5 is the Grevelingen, -4.5 is the Oosterschelde, -5.5 the Westerschelde).

Results, like for the grey seals, differed between the sub areas (*Figure 27*). In the north of the Voordelta (-2_VD_all and -3_VD_G), counted numbers after pile driving commenced are lower than predicted by the model. This is not the case for -4_VD_O west of the Oosterschelde, though numbers are low as numbers in this area clearly have been dropping since 2012. After the pile driving commenced, the harbour seal numbers in the Oosterschelde (-4.5_OS..) and even more so in the Westerschelde (-5.5_WS..) were higher than expected based on the model . In the Grevelingen (-3.5_GR_all) and the sub area around the Rotterdam harbour (-1.5_VD_E) numbers are dropping, though for the latter this is also predicted by the model; numbers there have been dropping since ~2017.

3.6 Strandings

Stranding data are collected by rescue centres and the general public, with little guidance as to what information needs to be recorded. A protocol or clear stranding scheme defining search effort and the type of measurements to be recorded is lacking. For example, length and weight of stranded specimens would be informative when trying to understand possible causes of such a stranding (i.e., malnutrition, disease). However, there is no official monitoring of such strandings and no study on the cause of death. Therefore, it is complicated to confirm or exclude links between changes in strandings and events such as the construction of the windfarms. Here we can only report changes that occurred in the construction period. Figure 28 depicts the annual number of seals found dead along the Delta coasts.

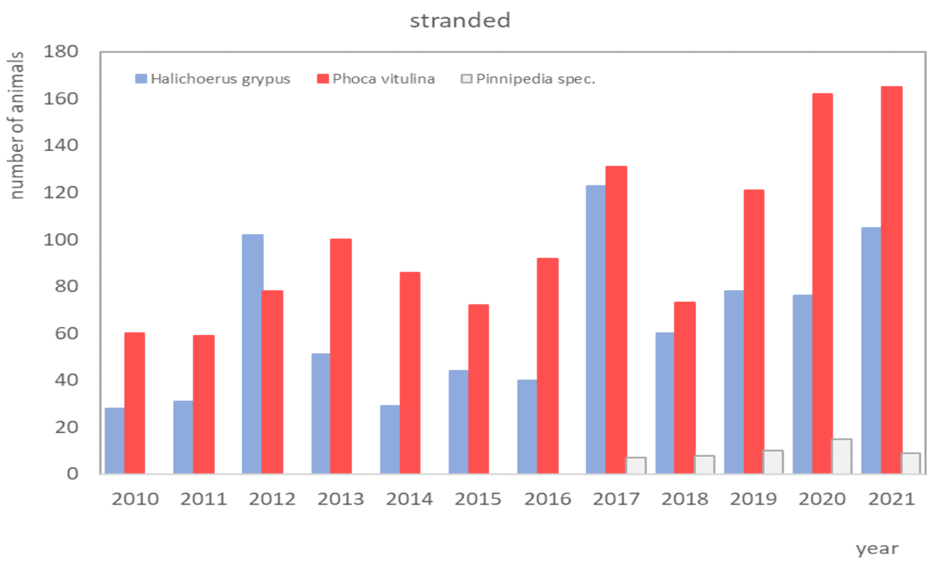


Figure 28. Annual *numbers* of seals found dead along the coasts of the Dutch Delta 2010-2021.

Clearly there is a rise in numbers, especially in harbour seals in 2020 and 2021, compared to earlier years. In lack of details on the stranding and of information on other construction or activities in the area it is hard to define if there might be a relationship with the pile driving or what might have caused the higher mortality in 2017 for example. When looking in more detail (discerning in age classes) an increase can be observed in 2020 and 2021 in mostly juvenile and to some extent sub adult animals found dead, and especially harbour seals.

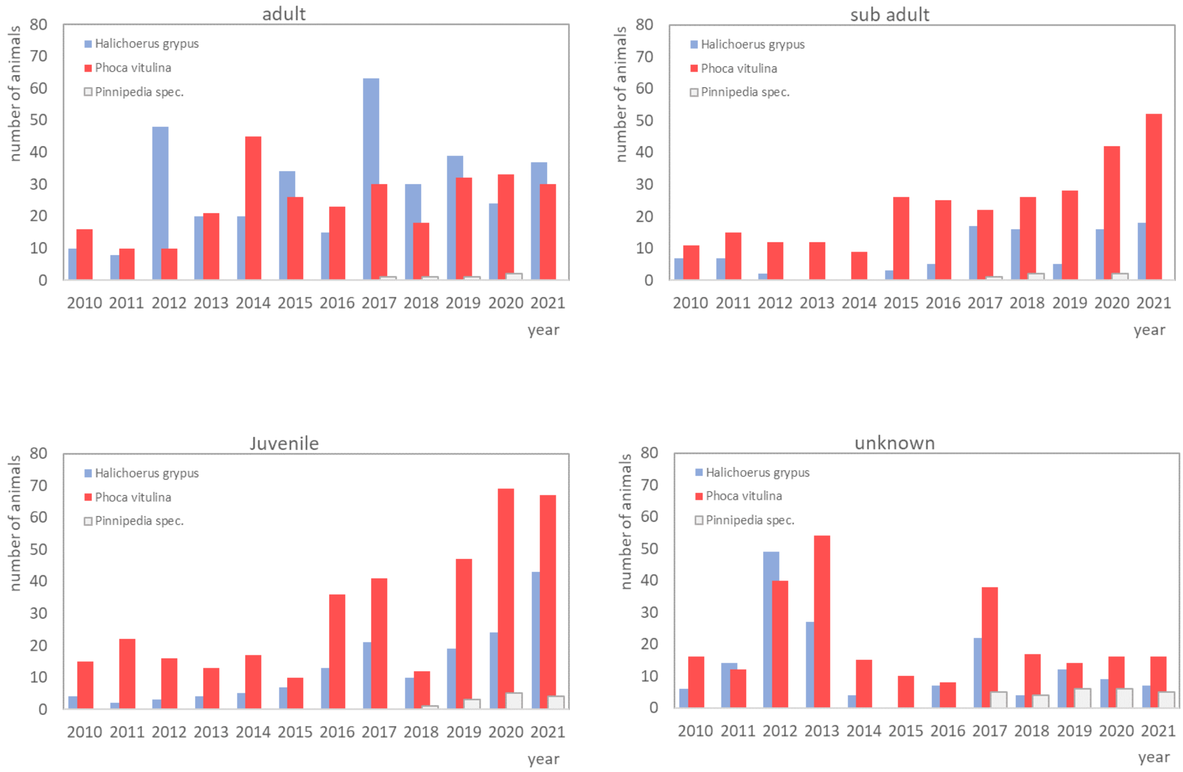
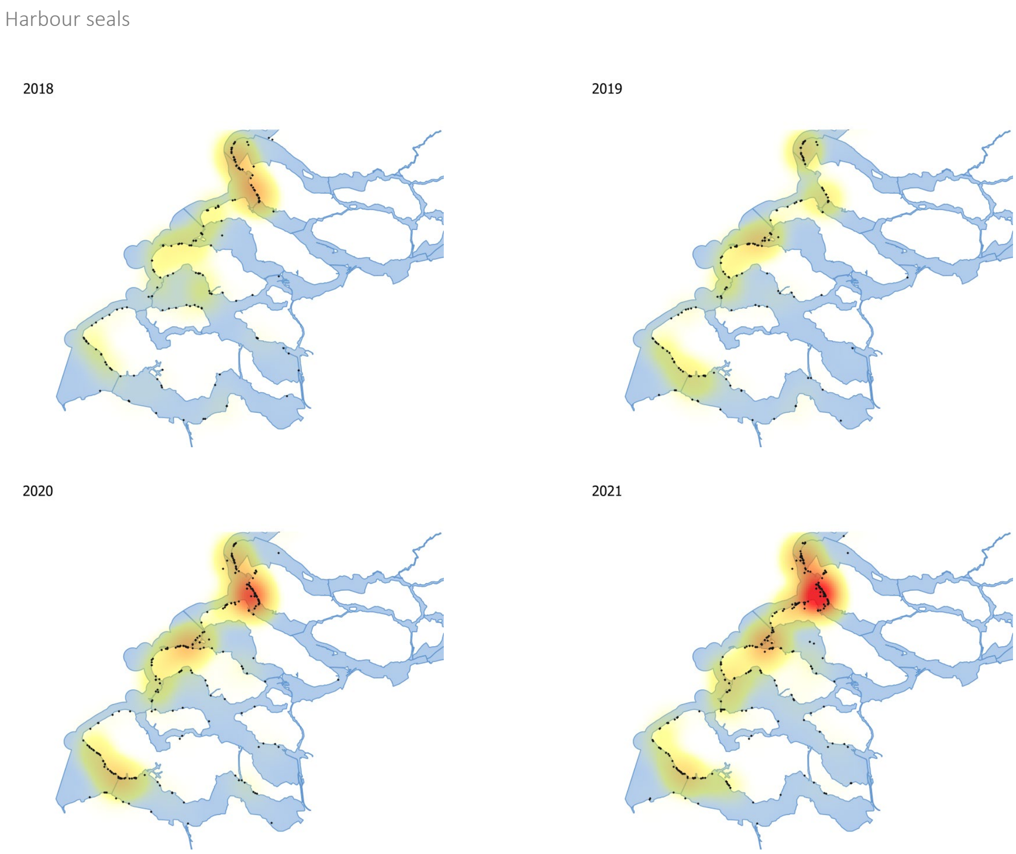


Figure 29. Annual numbers of seals found dead discerned by age classes.

When seals die, the current might influence where the animals strand. In Figure 30 we indicated the changes in stranding patterns 2018-2021 for harbour and grey seals. Here we see that dead seals are found along especially the marine coast of the delta area. Harbour seals are mostly found in the north near the Haringvliet, while grey seals mostly strand west of the Grevelingen where the highest concentration of grey seals haul-out.



Grey seals

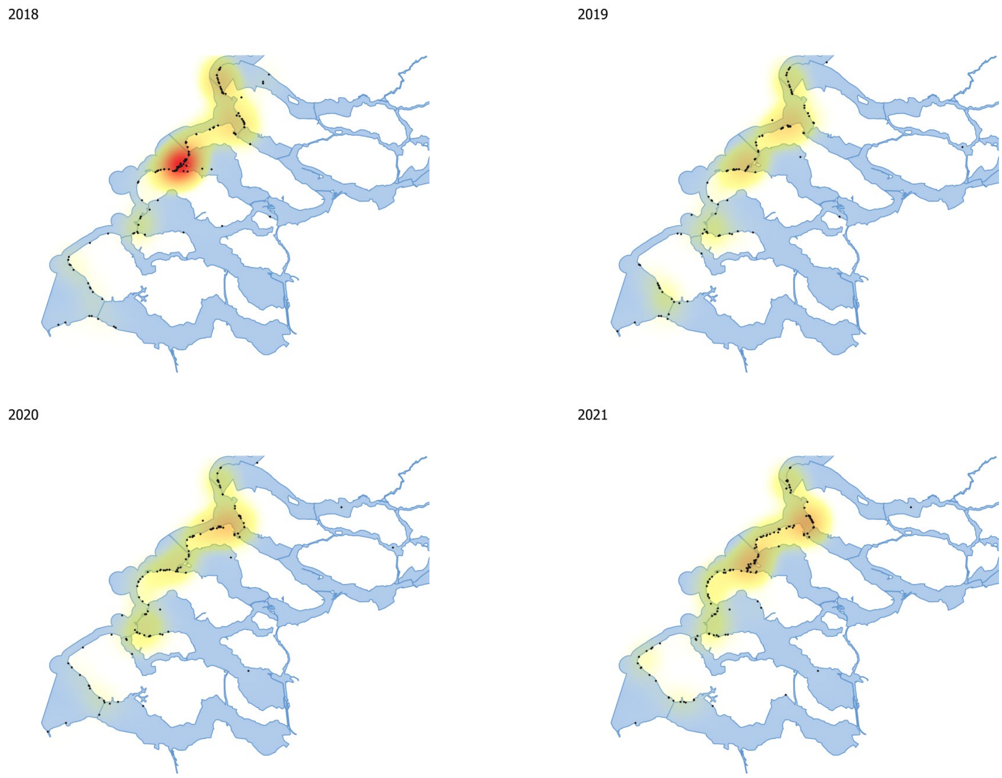
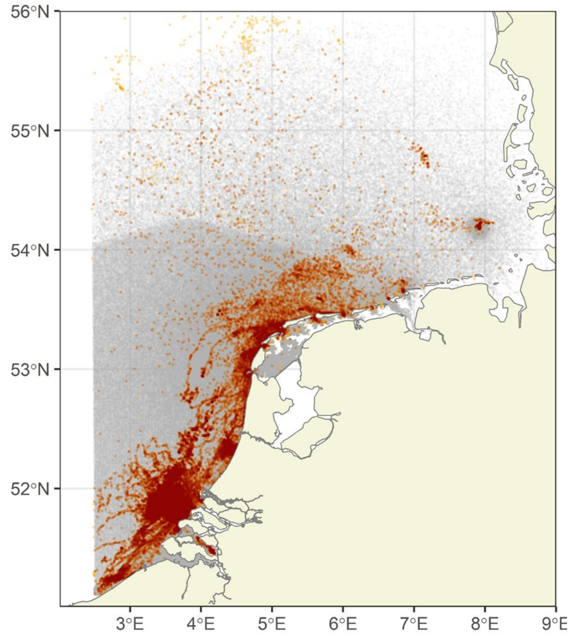


Figure 30. Distribution of dead stranded harbour (top) and grey seals (bottom) in the Delta area 2018-2021. Concentration is indicated with so called heatmaps, individual finding locations are indicated with a black dot.

3.7 Habitat selection

The seal density was modelled as a function of the environmental variables as shown in Figure 5. This habitat model was fitted based on a use-availability design, where the observed seal distribution was contrasted with environmental conditions at places seals could visit. The used and availability locations for both harbour and grey seal are shown in



Harbour seal Grey seal

Figure 31 The data used to model harbour seal (left) and grey seal (right) distribution. The orange points are the seal GPS locations, i.e., the "used" locations, and the grey points are the "availability locations"

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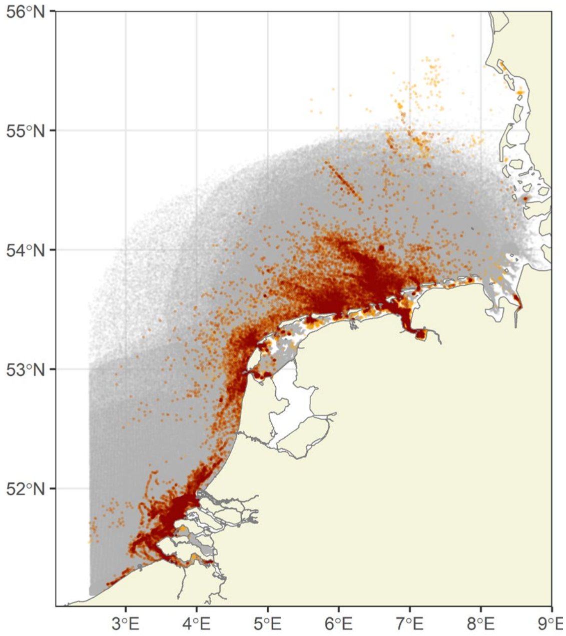

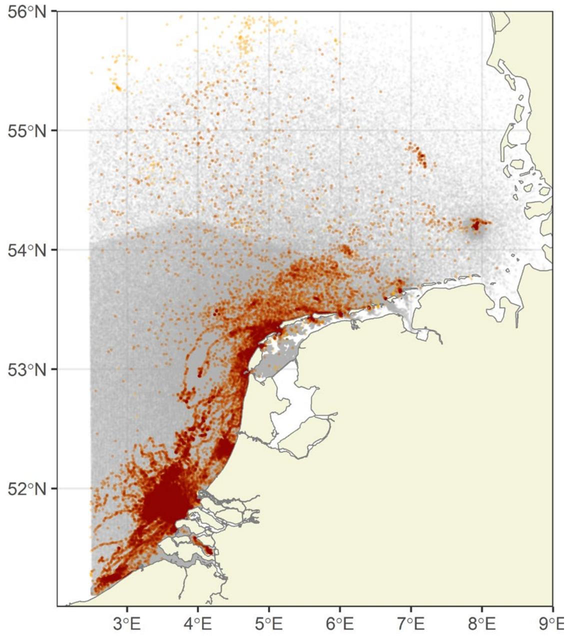

Harbour seal

Grey seal

Figure 31 The data used to model harbour seal (left) and grey seal (right) distribution. The orange points are the seal GPS locations, i.e., the "used" locations, and the grey points are the "availability locations"

Once the model was fitted to data from each seal species separately, this results in an estimate of the effect of each environmental variable on seal density (on the log-scale, see eq. 2). This relationship describes the strength of the seal's preferential selection for those environmental variables (Figure 32). The variable distance to the haul-out, shows (as expected) a negative relationship; seals are more likely to use places close to the haul-out site. In addition, harbour seals have a tendency to avoid the very shallow areas (<10m) and highest relative seal densities are found at ~20m depth. No strong effect of the %mud (on logit-scale) is apparent, and seals prefer regions characterized by a high topographic position index (i.e., 'peaks' and 'ridges'). Finally, harbour seals tend to avoid areas close to the Borssele wind park area Figure 32f.

The estimated habitat selection model can now be used to estimate seal density (Figure 33c). This seal density is built up of two layers: 1. The habitat model (Fig. Figure 33a, based on the relationships as shown in Figure 32) and 2. The latent field (Figure 33b)) which captures the residuals in the seals' spatial distribution that cannot be explained by the environmental variables. The estimated distribution of seals can now be mapped with the effect distance to the Borssele wind farm area (left part, Figure 33c) and without the effect of the wind farm (right part, Figure 33c). This reveals a slightly lower density in the direct vicinity of the wind farm area. Also the latent field (Figure 33c) shows predominantly negative values in the Borssele wind farm area, which suggests that that the effect of distance of the windfarm might be slightly underestimated.

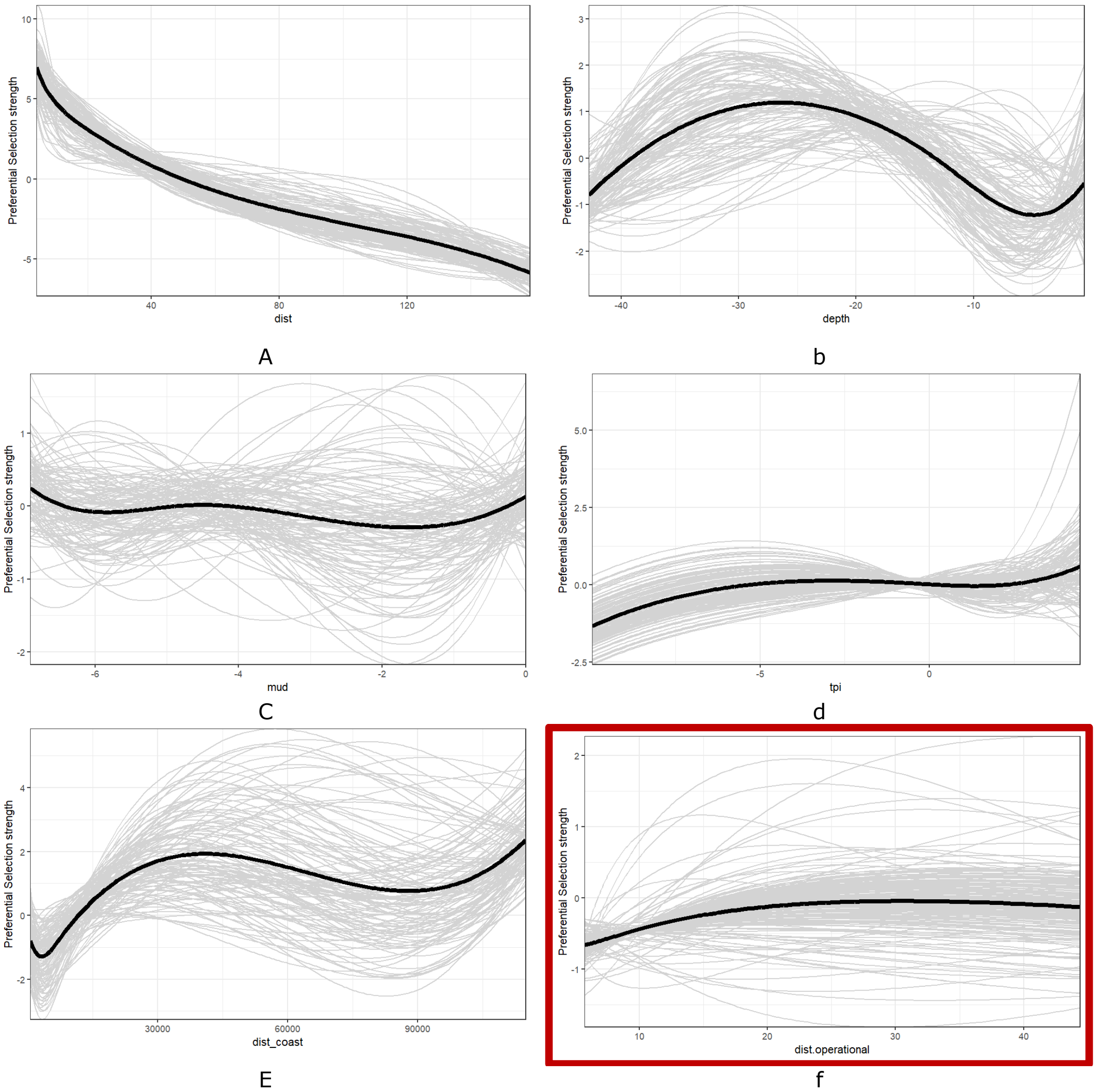

Figure 32 Harbour seals: Preferential selection strength (see eq. 2) as function of each of the environmental variables:
(A) dist = distance to the haul-out site (km),
(B) depth = depth the to sea floor,
(C) mud = %mud in the sediment on the logit-scale,
(D) tpi = topographic position index,
(E) dist_coast = distance to the coast (m), and
(F) dist.operational = distance to the a wind farm in construction or operation (km).
High values imply a higher use of those environmental conditions as expected (i.e. preference) and low values imply a lower use of those environmental conditions as expected. The grey lines represent the estimated function for each individual, and the black line the population average.

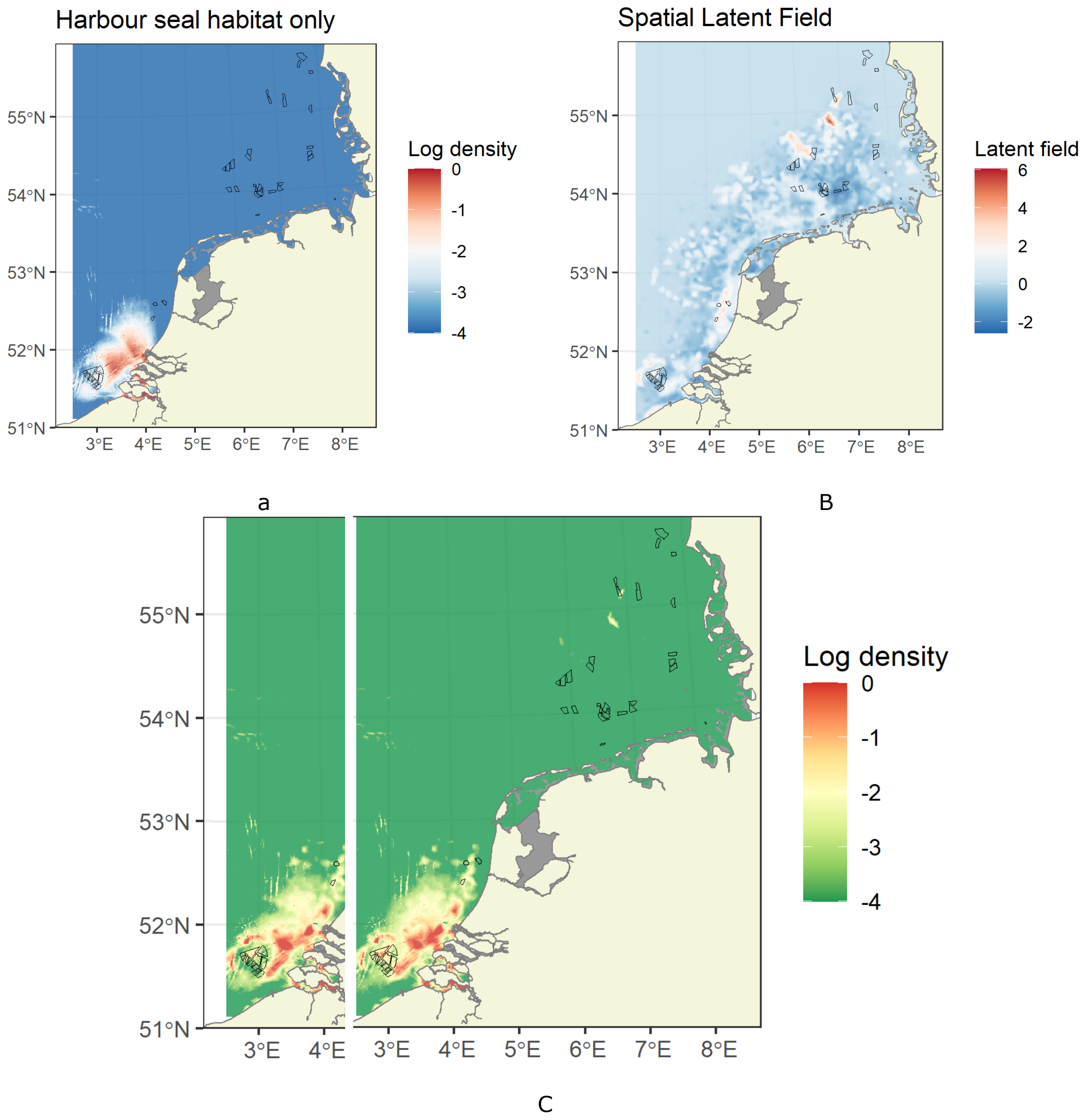

Figure 33. Harbour seals: a. Estimated seal distribution (log of density) based on the habitat model only. b. The latent field, capturing residual variation in seal density not explained by the habitat model. High values means that more seal GPS locations than expected (based on the habitat model) and low values means less GPS locations. C. Estimated seal distribution (log of seal density) based on both the habitat model and latent field and corrected for seal counts on the colonies. Estimated distribution is shown in the presence of wind farms (left) and in the (theoretical) absence of wind farms (right). Note that seal density is lower on the left, suggesting that seals avoid this area, which cannot be explained by the other environmental variables.

Similar to harbour seals, the model was fitted to grey seal tracking data and an estimate of the effect of each environmental variable on grey seal density was obtained. Also here the variable distance to the haul-out shows (as expected) a negative relationship, with seals being more likely to use places close to the haul-out site. In addition, grey seals have a tendency to prefer the deeper waters < -25 m depth. Grey seals avoid areas with high mud content and prefer regions characterized by a high topographic position index (i.e., ‘peaks’ and ‘ridges’). Finally, on average grey seals do not show a clear relationship with the Borssele wind park area.

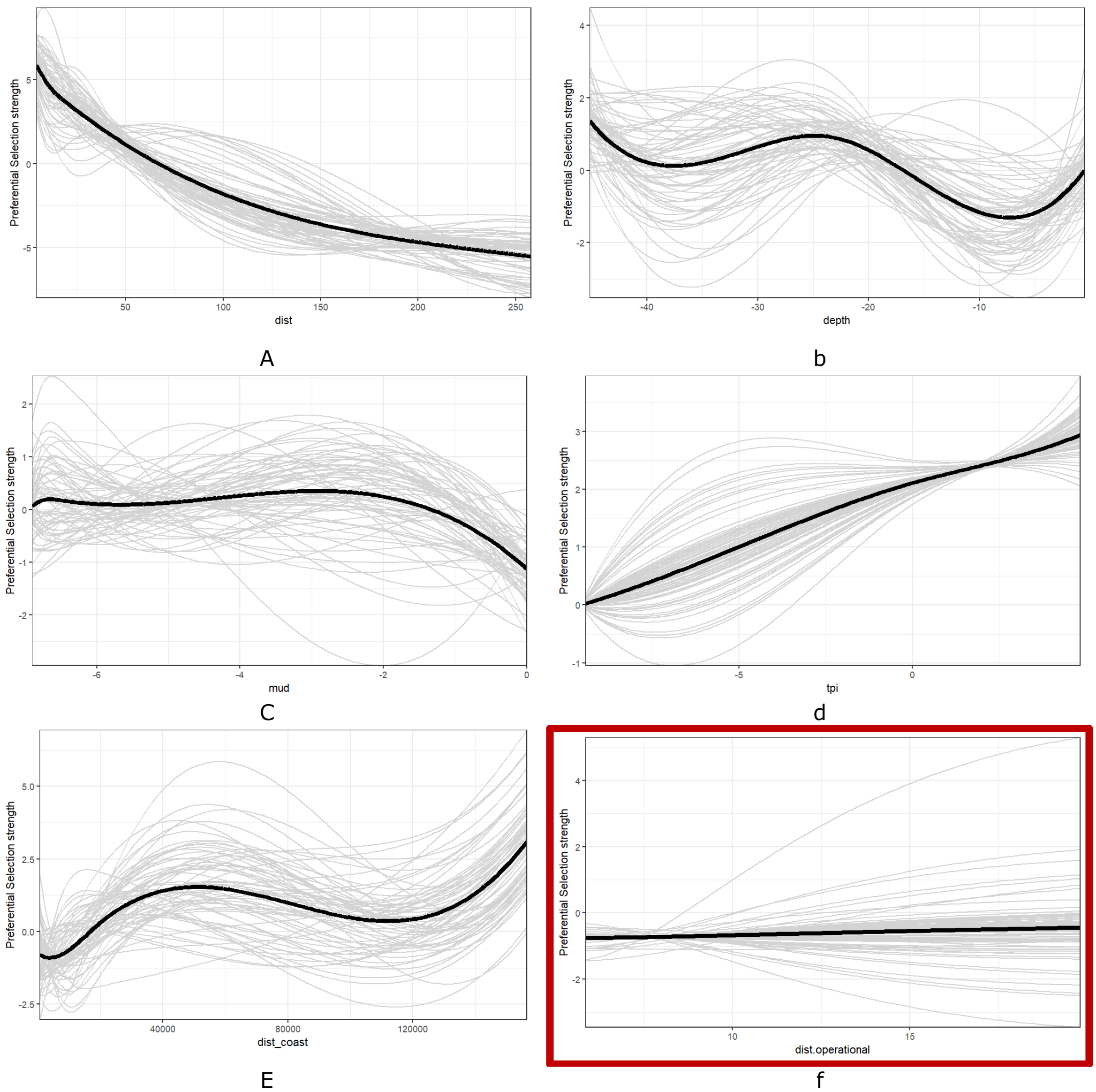

Figure 34. Grey seals: Preferential selection strength (see eq. 2) as function of each of the environmental variables:
(A) dist = distance to the haul-out site (km),
(B) depth = depth the to sea floor,
(C) mud = %mud in the sediment on the logit-scale,
(D) tpi = topographic position index,
(E) dist_coast = distance to the coast (m), and
(F) dist.operational = distance to the a wind farm in construction or operation (km).
High values imply a higher use of those environmental conditions as expected (i.e. preference) and low values imply a lower use of those environmental conditions as expected. The grey lines represent the estimated function for each individual, and the black line the population average.

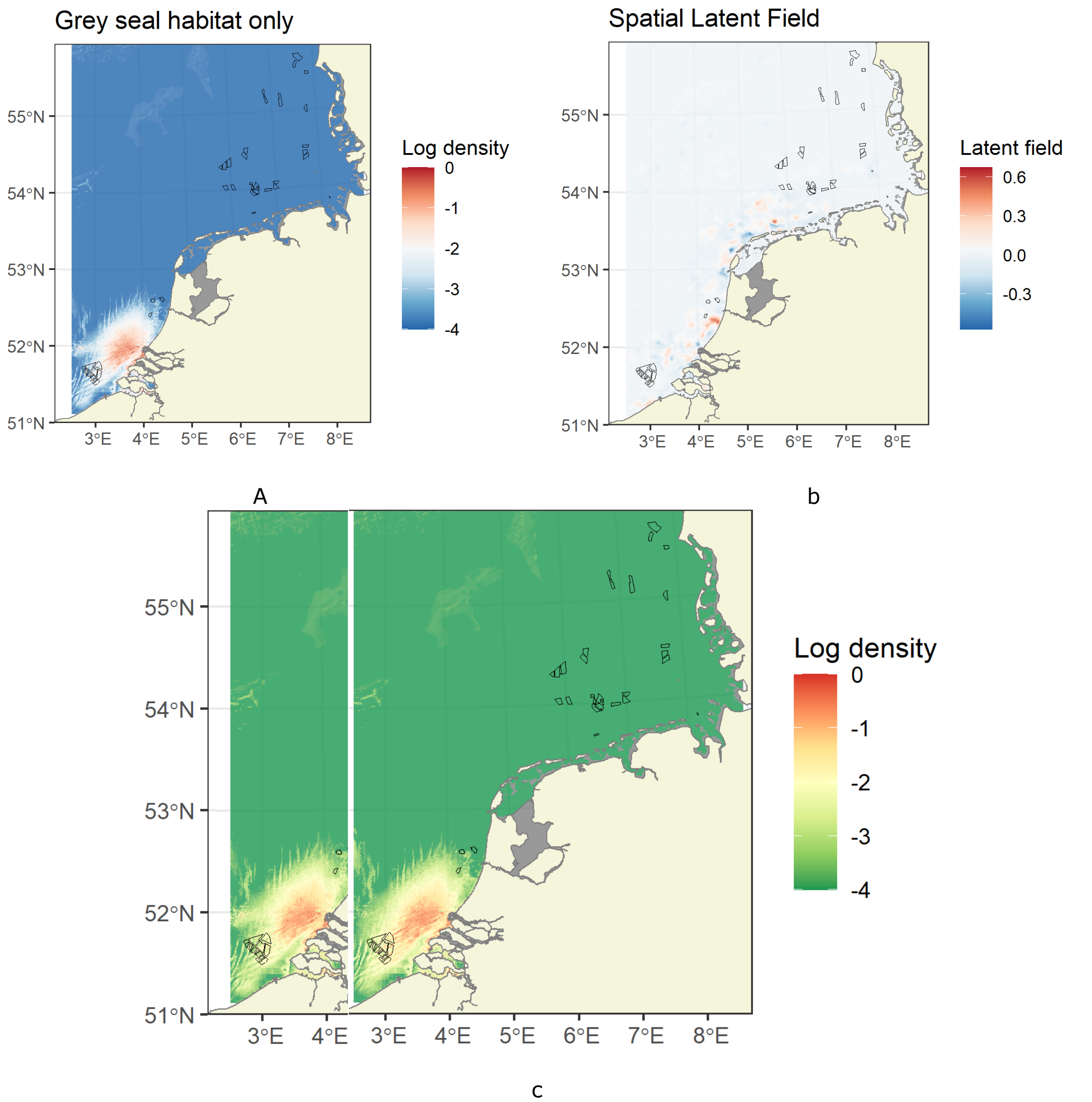

Figure **35**. **Grey seals**: a. Estimated seal distribution (log of density) based on the habitat model only. b. The latent field, capturing residual variation in seal density not explained by the habitat model. High values means that more seal GPS locations than expected (based on the habitat model) and low values means less GPS locations. C. Estimated seal distribution (log of seal density) based on both the habitat model and latent field and corrected for seal counts on the colonies. Estimated distribution is shown in the presence of wind farms (left) and in the (theoretical) absence of wind farms (right).

4 Discussion

4.1 General

Given the location of the Borssele wind farms, at a relatively short distance to important haul-out sites of both harbour and grey seals. This could have been a fruitful opportunity to test the effect of pile driving on the seals on the short term at sea and on the midterm on land. However, the overlap in construction with other neighbouring parks, even prior to tracking, and the fact that the area is one of the busiest shipping areas in the North Sea probably affected the results. Also, the majority of seals present in the area are temporary visitors who are potentially less faithful to the area than if the animals would for example be breeding there. Moreover, given the almost continuous construction of windfarms in this region, it is unlikely that the seals that were tracked were the most sensitive. We would assume that these animals would have moved away earlier.

4.2 Tracked animals

4.2.1 Fitness of the tracked animals

For both species the weight of the tracked animals was relatively low compared to animals tracked earlier (2005-2016). The sample size is low but almost significant, but too low to discern why this would be the case. However, it is tempting to expect that these seals are actually lighter either due to the fact that they, as temporary visitors, migrate more or due to the intense human use of the area compared to for example the Wadden Sea. There is very few (recent) data on the length weight relationship in seals and how this can vary. It would be worthwhile to study this in more detail and determine if actually either hypothesis would be viable.

4.2.2 General movements of the seals

Compared to earlier tracking data (grey lines in Figure 8 and Figure 10), there were fewer trips far offshore. This was particularly the case for the grey seals, where only one animal crossed over to the UK. The harbour seals remain close to shore, except for a few trips off shore (mostly by one male), especially after pile driving in Borssele 3&4 started (period 2-4 in Figure 9 and Figure 11). Changes in human activities at sea (shipping lanes, sand mining, fishing etc.) may influence the seals' distribution. However, not knowing the role of natural processes, for example what the animals in the area feed on and how the prey distribution might have changed, makes it difficult to be conclusive. Moreover, except for AIS to track ships, there are no data available on all human activities at sea, like some pile driving events, seismic surveys, stone deposits, military activities or fishing activities. This hampers the understanding of the observed changes.

4.3 Behavioural response to pile driving

This study looked at the effect of pile driving on the diving behaviour of grey and harbour seals. Like in earlier studies results were marked by large individual differences. Too little data was available to differentiate between seal species in the analysis.
Very few seals ventured into the vicinity of the construction site. Therefore, we recorded low numbers of exposures to pile driving at close distance. The closest distance from the construction location a harbour seal was found during pile driving was 8 km (Figure 15). Seals might have been even closer to the pile driving site, but during pile driving events there were often gaps in GPS location fixes. Possibly when fleeing the site, seals are less frequently at the surface or surface differently. The harbour seal at 8 km from the pile driving displayed high inconsistency in its diving profiles approximately 1 hour prior to the start of pile driving, a pattern also observed for grey seals exposed to pile driving of Luchterduinen en Gemini. This disorderly diving profile suggests some behavioural response, possibly

related to installation activities of the pile driving vessel. Around the time the ADD was turned on, approximately an hour before piling (Table 4), the descent speed further declined, suggesting the seal did not dive straight to the bottom but engaged in a horizontal movement, resulting in more V-shaped dives. The descent speed remained relatively low during and after the pile driving event. At the start of the pile driving, no other change in dive behaviour was observed. Behavioural responses are most easily detected when seals switch behaviour from foraging (high vertical descent speed) to transiting (low vertical descent speed). Since the seal already revealed a low descent speed prior to pile driving, this might explain the lack of disruption of that pattern.
The second nearest distance of a tracked seal to a piling site was 12 km. That seal did reveal a significant decline in descent speed, which does strongly suggest this individual did respond to the pile driving. This pattern, a decline in descent speed, has often been found for grey seals exposed to pile driving of Gemini and Luchterduinen.
The next closest distances were at 14 km and beyond. No clear and consistent changes in dive behaviour were observed for those distances, although there were a few instances of significant changes.

4.3.1 Behavioural response and Sound Exposure Levels (SEL)

This study also investigated the relation between the change in descent speed and estimated (modelled) broadband single strike Sound Exposure Level (SEL). Since the tracked seals rarely ventured into the vicinity of the pile-driving site, there were insufficient data to describe the relationship between change in behaviour and SELs. Based on a study for Luchterduinen (Aarts *et al*., 2018; Brasseur *et al*., 2018b), grey seals revealed a behavioural response when sound exposure levels exceeded 130 dB re 1 μPa^{2}s and on a few occasions between 120 and 130 dB re 1 μPa^{2}s. In this study, very few tracked seals were exposed to SELs values greater than 130 dB re 1 μPa^{2}s.

In several occasions we did observe statistically significant behavioural changes at the onset of pile driving at SELs below 130 dB re 1 μPa^{2}s. It can, however, not be excluded with certainty that such (significant) behavioural changes occur by chance, and it is also plausible that some of these events occurred as a result of faulty or ineffective mitigation measures (e.g., gaps in the bubble curtains). There were indeed a few piling events where multiple individuals showed a significant behavioural change at larger distances i.e. lower modelled SEL values, but this was not investigated further.

One of the aims of this study was also to investigate whether estimated SEL, weighted for known hearing capacity, or estimated unweighted SEL best explained the behavioural changes. Weighted single strike SEL estimates for phocids (SELss,pcw) were approximately 22 dB lower compared to the unweighted SELs (Oud and de Jong, 2021). For harbour porpoises (SELss,vhf) the average reduction was much larger, namely 67. This is due to the porpoises low sensitivity to the dominant frequency of pile driving sound, while seals are more sensitive there. While weighted single strike SEL are lower in absolute sense, the weighted and unweighted SEL are correlated. Hence, given the large individual variability in behavioural responses it would be practically impossible to determine empirically which metric (weighted or unweighted) is most suited to explain observed behavioural changes of the seals.

Overall, we can conclude that in this study we were unable to collect sufficient exposures to pile driving at close distance to accurately estimate the distance or SELss at which seals are affected by the pile driving operations. There are several possible explanations for these.

1. Since the mitigation measures reduced the sound exposure levels (SEL) as predicted in (Stöber and Thomsen, 2019), and smaller effect distances are to be expected, the area (impact area) and the chance of seals actually being in the impact area are also reduced.
2. Compared to GEMINI for example, the construction site is relatively close to shallow waters near shore, thus lower or at least attenuated SEL are expected on the east side of the wind farm area, near the seal haul-out sites.

3. The region around the Voordelta is one of the most intensive shipping areas in the North Sea and the construction of the Borssele windfarms was not the only activity in the region. As explained, at least two other windfarms were pile driving in the same period (SeaMade and Northwester) and other parks were being finalised or started (Rentel and Norther). Also, other offshore wind parks were constructed well before this study on the Belgian side of the area, e.g., Thornton Bank was already constructed in 2007 and construction was almost ongoing since then. Seals in the area might have habituated to the ambient human noise levels present or adapted their behaviour. Moreover, more sensitive individuals might have left the area prior to this study. As a consequence we can assume that the seals in the area (and the ones tracked for this study) were not naive to the situation and might also not be representative for all seals using the Delta area during undisturbed conditions. As pile driving was ongoing prior to the tracking we could assume most sensitive seals might have left the area. This has been observed for seals (Edrén *et al.*, 2010), where continuous exposure led to lower densities over time.

Despite the proximity of the wind farm to several know haul-out sites very few seals were observed to even approach the area, irrespective of piling. As mentioned, the tracking data collected in earlier studies showed a distribution farther off shore than the current tracks (Figure 10 & Figure 11). Potentially a more in-depth study would help identify differences between the tracked animals. At the moment we can only speculate about the cause, the intense and ongoing construction prior to the tracker deployment is a likely explanation.

As so little data was obtained of animals in and around the pile driving area, we were not able to pursue an analysis on the effect of context (e.g., type of individual, moment of the foraging trip) on the exposure.

4.4 Surveys

Though monthly surveys of both seal species have been carried out for decades, there is relatively little information other than their changing numbers on the colonies in the Delta Area. In this study we do not attempt to explain the population development (the numbers being mostly defined by animals feeding but returning to other areas to breed), but rather describe the changing numbers in the different sub areas. The results show that these sub areas have variable trends, mostly growing in the past decades and certainly compared to the 1970-1990 when only a few harbour seals were observed. Still some areas are showing recent decrease. Both species display this in the Voordelta west of the Oosterschelde, this seems to be going on since around 2012. Note that by then almost 100 turbines were constructed in the Belgian parks, the first park in that region, Thornton Bank, was constructed in 2007 and operational in 2009. Again, without records of how human use of these areas or natural processes might have changed, it is difficult to explain why this might be the case.
The modelling showed that though differently for the different sub areas, the numbers present did depend on the season and year. Interestingly, the number of seals counted did not follow the expected trend during the pile driving period in the Borssele windfarms. This indicates that distribution and numbers in subareas changed during the pile driving period. In some sub areas numbers were lower than predicted and it would be obvious to interpret this as animals leaving the area. For grey seals this seemed to be the case in some areas in the Voordelta but not in the area with the largest numbers (west of the Grevelingen). There numbers raised unprecedentedly and far above the modelled expectations. In harbour seals numbers after the pile driving started are below expected in the Voordelta, but we also observe rising numbers, rather in the more inland waters of the Oosterschelde and Westerschelde. Potentially, the higher numbers could be misleading to the assumption that more seals are in the area whereas it could be the result of animals avoiding underwater noise. Fleeing, so to say, the water where sound is propagated much better than in air.

4.5 Stranding data

Compared to earlier years, the number of animals found dead in the Delta area were higher in 2019, but even more so in 2020 and 2021, where the number of harbour seals were twice as high as in 2018, in grey seals the numbers in 2021 raised about 50% compared to 2018. For harbour seals this is mostly caused by the deaths of more young animals. In grey seals, more adults were found. Striking is the raise in numbers found dead in 2017. It is not clear what might have been the cause. Unlike the animals hauling out, the location of strandings is quite dependant on the current. Potentially this explains the distribution in strandings. The relatively high numbers in the north might be the result of animals floating there if they died at sea. On the other hand, dead animals are not studied and effects of disease of for example bycatch cannot be excluded. Given the continuous exchange of seals with other areas (i.e. The Wadden Sea, France and the UK) and the continuous variation in numbers observed, it is difficult to link these numbers directly to a local "population" of either harbour or grey seals. A more detailed study on how the number of animals found dead relate to the number observed remains to be carried out.

4.6 Distribution model

The avoidance of (or attraction to) an offshore wind park could either be caused by natural conditions at the location or could be the consequence of the wind farm and related human activities. By including environmental variables into the habitat-association model, this study attempts to account for these confounding natural environmental variables in order to extract the effect of the offshore wind park. This analysis shows an avoidance of the wind farm area (during construction (with a bubble curtain) and operation) by harbour seals up to approximately 10 km. No significant effect was apparent for grey seals. The study by Russel *et al*. (2016) demonstrated an avoidance up to approximately 40 km for harbour seals during pile driving, but there the piling was not mitigated, hence most likely explaining the larger impact area. Moreover, the limited number of seals in this study did not allow us to study the effect of piling alone.

For a single park it is challenging to estimate an effect, because it could be that not all relevant environmental variables are included in the habitat-association model or that the maps of environmental variables (e.g., sediment type) are of insufficient quality. In this study, we tried to account for this effect by including a spatial latent field in the model, which can capture residual spatial pattern of the tracked seals. However, the downside of such a latent field is that it could absorb too much of the variation in seal density, removing or underestimating the effect of the other environmental variables, including distance to the wind farms. Despite this conservative approach, a significant effect of distance to wind farm was still found for harbour seals, which further supports an avoidance of the wind farm area. In future studies it would be advisable to extend the analysis to the entire North Sea, including more tracking data from regions near other wind farm areas.

In this analysis, we did not differentiate between parks in construction and operation. The 'Borssele area' is an assemblage of several Belgian and Dutch wind parks, some were under construction during the tracking period and others already operational since 2007. Human activities in this region were almost continuously ongoing. Also, only information on pile driving in 2019 and 2020 was available. The Borssele region is an industrial complex, with several other activities related to the wind farms, like shipping, seismic surveys, detonation of explosives, scour protection placement, etc. To differentiate between the effect of operation and construction, it would be necessary to look at parks located in isolation and analyse tracking data well before and after the construction of the wind farm, which was not possible within this project.

This study, but also our tracking data from other regions (ranging from 2007 onwards), suggest an avoidance of the wind farm areas. At the same time, some tracked individuals were observed to be (temporarily) attracted to wind farm areas, foraging near the mono piles for several weeks or months. For example only two individuals out of 148 seals tracked in the Dutch Eems 2009-2011 visited the new Alpha Ventus windfarm (Russell *et al*., 2014). This might be due to differences in personalities, some being ‘brave’ and others being more responsive, as observed in many other species. So far, studies on attraction (Russell *et al*., 2014) and avoidance (Russell *et al*., 2016) have been studied in isolation. To understand the impact of the expansion of offshore wind farms (and other human activities at sea), it would be advisable to take a more holistic approach and investigate net effects (positive and negative) at population level. A habitat model as presented here could be suited for this, because it could capture both processes simultaneously. When fitted to a large data set, it would be possible to estimate the temporary (during construction) and permanent (during operation) population reduction caused by offshore wind farms. Furthermore, it would allow for an impact assessment for future wind farm locations, by estimating the reduction in population density caused by habitat loss.

5 Conclusions and recommendations

At the onset of the study, information on the exact start date of the construction of Borssele 1-4 was missing, and no information was available on the construction of the other wind farms in that region or other related human activities. As a result, this study on the influence of pile driving for wind turbine foundations at sea on seal behaviour and distribution was impaired. Also, the sound of piling was mitigated, reducing the ability to measure an effect. Due to a lack of sufficient exposures at close range, partly due to avoidance of the wind park, this study was unable to estimate a dose-effect relationship. Even if a dose-effect relationship could be estimated, it is questionable if the exposed individuals would be representative for the population.

The harbour and grey seals weighed during tagging in 2019 were lighter than seals weighed in earlier years, but this effect was not significant, possibly due to small sample size. A number of the few seals that approached the pile driving within 35 km did change diving behaviour, but in some cases before the actual pile driving commenced. Trends in number of seals hauled out in most areas changed. The number of seals were either higher or lower than could be expected and varied, depending on the sub area and species. And finally, more dead seals were found following the pile driving period, though it is complicated, without further information (i.e. on cause of death and exchange with other areas) to link this to changes in numbers in the Delta area and changes herein due to pile driving activities.

Observed changes in this study could be the direct or indirect result of the pile driving in the Delta area, but could also be caused by any of the many other human activities (including other windfarm related activities) or even natural changes. Repeatedly during the analysis, it was obvious that reference data on an undisturbed baseline pre-construction period (*t0*) could not be obtained, especially in an area as intensely used like in the Southern North Sea. This confounds any effects of pile driving, but could be partly accounted for by having detailed records of all the other human activities, like (seismic) surveying, shipping, and construction activities. To some extent, this issue was circumvented by using the habitat model and including the latent field. Despite this conservative approach, the study showed avoidance of harbour seals for the Borssele area.

5.1 Future studies

The distribution and behaviour of seals in the North Sea is influenced by a large variety of both natural and anthropogenic environmental variables. In the absence of anthropogenic activities, one could attempt to estimate how seals are influenced by their natural environment. Then, when human activities occur, it might be feasible to investigate how seals change their behaviour. Such conditions are unlikely in the Southern North Sea, particularly in the Delta region, which is one of the most heavily used areas of the North Sea. As a consequence, a suitable baseline to detect any changes is no longer available.

One recommendation for future studies is to use a more holistic approach. The distribution of seals is known to be strongly influenced by several natural environmental variables, like sediment type and depth. These environmental variables are important because they influence for example the availability and accessibility of prey to these top predators. Sandeel for example, has a strong preference for coarser sediments, potentially explaining the preference reflected in the seal distribution and the importance of this prey for the seals. Bathymetry influences the cost (in time) to reach the bottom and forage, and hence, fewer seals will be found in extremely deep water. Similarly, anthropogenic activities could also influence the availability and accessibility of these prey, either directly (e.g., limiting the time seals could forage undisturbed), or indirectly (e.g., creating a landscape of fear for either prey or predator). These effects could be revealed in changes in density relative to a baseline habitat preference model. When concentrating on a specific region (e.g. the Voordelta), it is extremely challenging to differentiate between the multitude of natural and anthropogenic processes. Instead, we propose to use all tracking and survey data available, and investigate how the seals' distribution is shaped by the different anthropogenic activities. For example, the period of construction and operation of all offshore windfarms constructed in the southern North Sea during the past decades was collected (Figure 36). It would be possible with our longstanding tracking dataset to estimate how these activities influenced the density of seals and by doing so, estimate the overall change in the availability of suitable habitat for top predators like seals. A similar study could be carried out for shipping activities recorded by AIS or for other activities. The strength of such an analysis lies in the accumulation of the data and cumulative effects these activities have on the distribution and behaviour of seals.

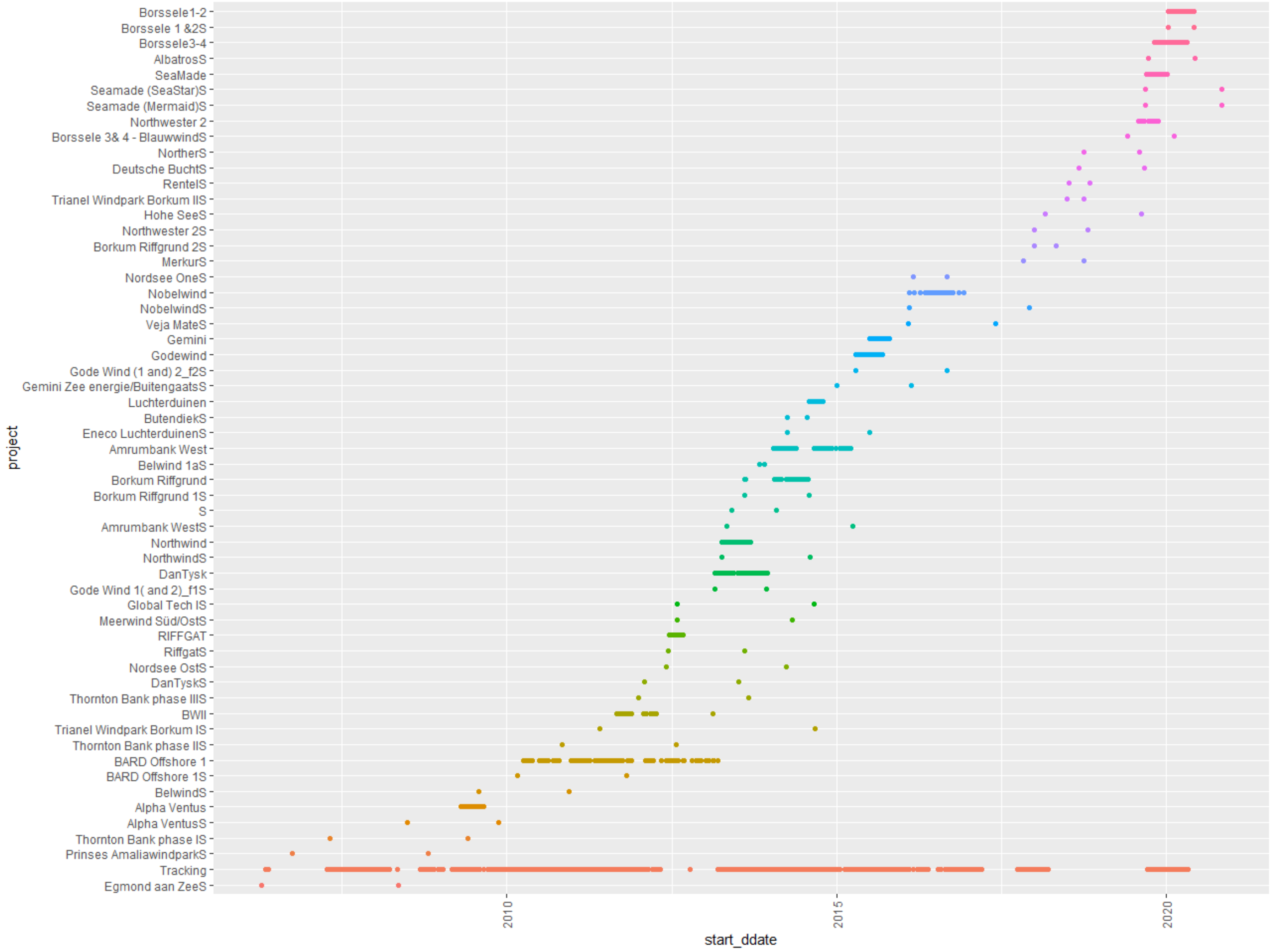

Figure 36 Timeline of construction of windfarms in the Southern North Sea compared to the seal tracking data of WMR (orange line below). Start and end of the consturuction is indicated by a dot, pile driving by a line (when data is available). Every line represents one windfarm (project). On the x-axis time (2005-2022) is indicated. Windpark names followed by capatical S represent those with summary data. For some parks, both summary data and detailed piling logs are available, these park appear twice in the figure.

5.2 Recommendations

Regarding environmental data and scale of offshore impact studies

- Develop a comprehensive database of all major human activities at sea (e.g., construction work, shipping, seismic surveys), ideally at North-Sea level. Comparable to the ecological monitoring schemes, authorities responsible for permitting activities at sea could create public records of where when and how to facilitate the study of possible effects of these activities, also in hindsight.
- Link species distribution data with all human activities and investigate how it reduces habitat quality at the population level. Analyses for single wind parks are unlikely to be fruitful, since a proper t0 (complete undisturbed condition prior to construction) can no longer be obtained and statistical power based on single park will be too low (sample size = 1).
- Study the effect of human activities on marine mammals in an ecological context. Seals (and other marine mammals) spend the vast majority of their time finding and catching prey, and population carrying capacity is largely driven by overall prey availability. Changes in prey availability and distribution is expected to influence how and when seals respond to human disturbance. To capture this, information on prey should be collected.

Regarding the data collection, for studies of seals as an indicator for the changes in the marine environment, the following recommendations can be given

- Continue population monitoring and detailed analysis to better understand population changes, and serve as an indication of change at sea
- Collect more detailed stranding records and carry out necropsies on a subsample of the seals stranded. This would help in understanding general health issues and causes of death, but also provide updated information on basic population parameters such as mortality, fecundity and growth.
- Tracking seals more consistently. This would provide information on both natural (including annual changes etc) and human effects on behaviour and distribution.

Quality Assurance

Wageningen Marine Research utilises an ISO 9001:2015 certified quality management system. The organisation has been certified since 27 February 2001. The certification was issued by DNV.

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Justification

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Project Number: 4316100253-WP4/5

The scientific quality of this report has been peer reviewed by a colleague scientist and a member of the Management Team of Wageningen Marine Research

Approved: Steve Geelhoed
Reseacher

Signature:

Date: 3 November 2022

Approved: Drs. Jakob Asjes
MT Member Integration

Signature:

Date: 3 November 2022

Wageningen Marine Research
T +31 (0)317 48 7000
E: marine-research@wur.nl
www.wur.eu/marine-research

Visitors' address

- Ankerpark 27 1781 AG Den Helder
- Korringaweg 7, 4401 NT Yerseke
- Haringkade 1, 1976 CP IJmuiden

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