Measurement of effects of piledriving in the Borselle wind farm zone on the seals in the Dutch Delta area

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 C055/22

Measurement of effects of piledriving in the Borssele wind farm zone on the seals in the Dutch Delta area

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

Sophie Brasseur, Geert Aarts, Jessica Schop

Wageningen Marine Research
Den Helder, October 2022

Confidential: No
Wageningen Marine Research Report C055/22

Keywords: grey seal, harbour seal, piledriving, tracking, surveys stranding

Client: Verkenning en Planuitwerking RWS Zee en Delta
Attn.: Aylin Erkman
Postbus 556
3000 AN Rotterdam

This report can be downloaded for free from: https://doi.org/10.18174/576980
Wageningen Marine Research provides no printed copies of reports

Wageningen Marine Research is ISO 9001:2015 certified.

Photo cover: Aerial picture of the tagging of seals in the Delta 19-09-2019. Pim Wolf DMP

Contents

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, ultimately covering approximately 25% of the Dutch part of the North Sea. Especially as similar intentions have been declared by the other North Sea countries.

In this study 10 harbour and 10 grey seals were tracked to study the effects of pile driving in the Borssele wind parks (1-4) on the seals' behaviour. Additionally, long term monthly counts of seals on land (data provided by DMP) and records of stranded animals (collected by volunteers and seal rescue centres, available on waarneming.nl) were inspected to detect changes in trends. The study is commissioned by the WOZEP programme of RWS.

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 was at 8 km. This harbour seal started changing diving behaviour before pile driving commenced. The grey seal closest to a piledriving 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 for Luchterduinen and Gemini, the distances at which seals 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 always 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. One likely explanation is that seals avoided the area. Before the GPS trackers were deployed, the construction of several other windfarms was already ongoing, and this may have driven the seals away from the park towards other foraging 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 Voordelta however, contrary to more southern haulouts, unusually high numbers were recorded there on land in 2021. This suggests that grey seals spent more time on land to avoid being in the water where sound is louder or perceived conditions elsewhere, for example in the United Kingdom or Wadden Sea area to be less favourable compared to the Voordelta.

Strandings: More dead seals were found on the coasts in the Delta in the two years following the piledriving. 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 and changes in numbers hauled out and stranded were found that coincided with the piledriving, 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 for future studies. 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 meaningful scale (both spatially and temporally). By combining all available data (both seal tracking and wind farm construction data), 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 approximately 25% of the Dutch North Sea will be filled with wind parks.

Despite the perceived urgency, there is relatively little knowledge on the effects of these ambitious 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, 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 mills 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 piledriving, most studies have been commissioned to study only the effect of piledriving. 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 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. 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 come to the surrounding waters to feed, while migrating annually 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 and, providing the granted protection from human threats is continued, these might remain. (See chapt. 2.3 and 3.1. for more detail on population developments).

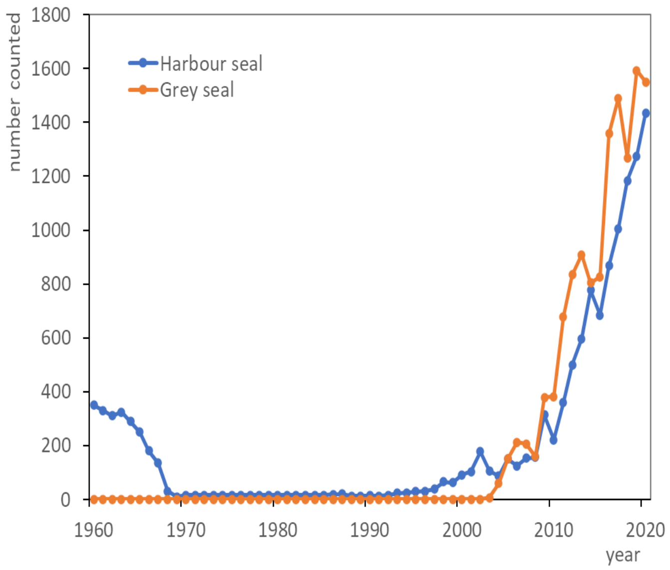


Figure 1. Development of the number of seals counted in the Dutch Delta area 1960-2021 (data: Compendium voor de Leefomgeving (clo.nl))

1.1.2 Underwater sound and other potential effects

As mentioned before one of the most intense single sound during construction is potentially piledriving, 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 piledriving of offshore windfarms typically peaks between 0.5kHz and 1kHz, 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 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 piledriving 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., 2018b). There was however large individual variation, with behavioural changes observed between 10 and 50km away from the piledriving site. The construction sites in previous studies (Luchterduinen en Gemini), were respectively 40 and 60 km away from haul out sites. The construction of windfarm Borssele is only ~20 km away from important harbour and grey seal haulouts in the Dutch Delta, and thus provided for a unique opportunity to study behavioural changes of the seals using the area. However, in piledriving 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. 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., 2018b; 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. Depending on the seals' site fidelity, it is moreover likely that animals that would not readily change feeding area, for example, are likely to be exposed to such disturbances for longer periods than migrating animals.

Though 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 the coastal ecosystems.

1.3 Research questions

In this project, seals were tracked with the aim of observing potential behavioural changes in relation to the piledriving activities of the companies *Ørsted* and *Blauwwind* in the Borssele wind farm area. In addition, existing monitoring of the seals hauled out in the Delta area and records of strandings were studied to evaluate potential effect at the larger scale. Specific research questions were:

1. How are the individual harbour and grey seals affected in their behaviour by the underwater sound caused by the piledriving 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 haulouts, can this be related to the behaviour of the tagged individuals?
6. What is the effect of mitigating measures?

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.

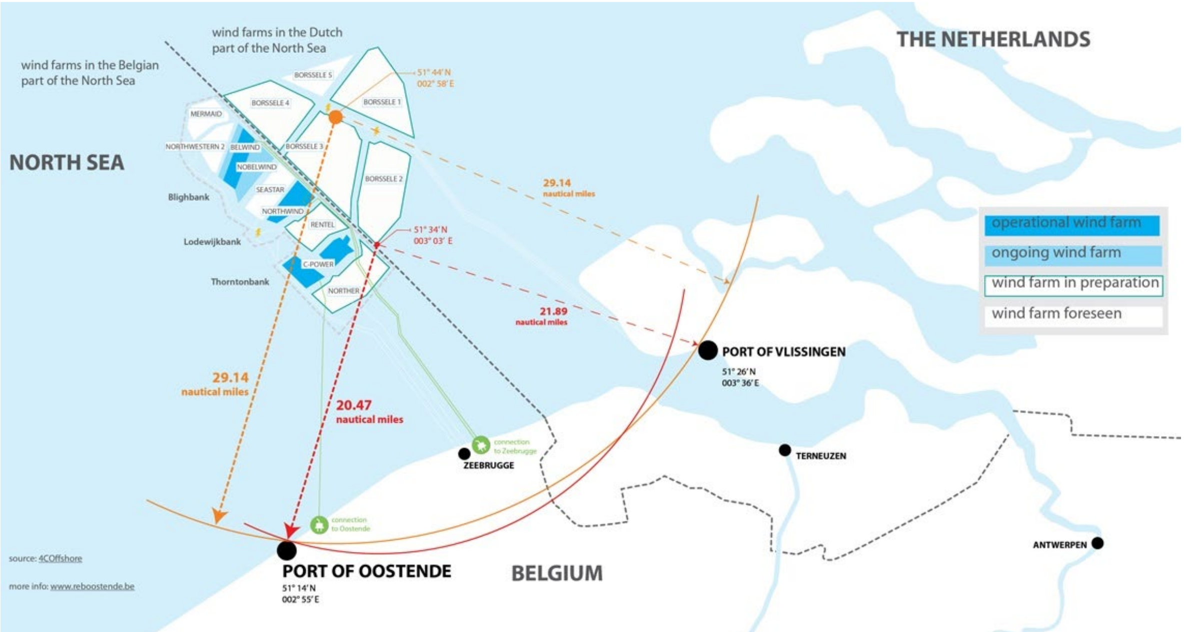


Figure 2. (https://deepresource.wordpress.com/2020/01/14/first-monopiles-installed-at-borssele-offshore-wind-project/)

The Borssele area is adjacent to the Belgian windfarm zone, which has been in construction since 2007, including the latest sites of which the piledriving 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 25km² (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 235.8km² (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 Delta Milieu Projecten and stranding records of dead seals made available via waarneming.nl.

Table 1. Overview of the timing of construction and data collection between 2018 and 2021.

	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 PILEDRIVING (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																																	
Seal surveys					*										**		*										**		*	*			
Strandings																																	

Survey: *=incomplete; **= financed by this project

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. 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 cm3) 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 piledriving of the two Dutch windfarms exploited by *Ørsted* and *Blauwwind* (Figure 3). The piledriving 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 piledriving 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 piledriving 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 piledriving 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

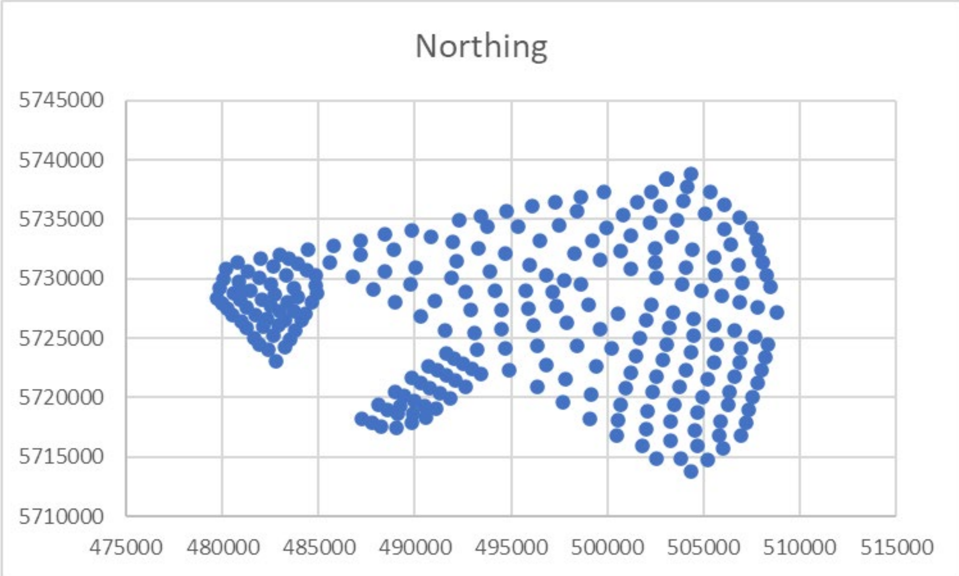


Figure 3 (to be replaced) Map showing position of piles of Northwester, Seamade, Borssele 3 & 4 (Blauwwind) Borssele 1 &2 (Ørsted) also add Norther and Rentel

This study was initially commissioned 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 the company WaterProof.

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 piledriving 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.

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 Piledriving	01:39:00	01:58:00	02:31:00	02:11:00	01:35:00	01:57:00	01:35:00
Average duration Piledriving	02:05:44	04:05:35	03:41:10	03:51:30	02:18:22	03:57:30	02:53:14
Max duration Piledriving	04:57:00	21:21:00	06:51:00	11:48:00	04:43:00	05:58:00	21:21:00

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 piledriving started, in average they were started a bit more than 20 mins 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 Behavioural response analysis of tracking data

2.2.1 Processing seal dive and tracking data

The dive depths measured by the pressure sensor in the tracker were recorded every 4s, 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 1.5m depth and the following first depth measurement above 1.5m 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., 2018a; Brasseur et al., 2018a; Brasseur et al., 2018b), the 0% and 100% time-points represented the estimated time the seal crossed the 1.5m depth line, and hence the time difference between 0% - 100% is on average the dive duration minus 4s.

2.2.2 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 35km 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.

2.2.3 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.

2.2.4 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 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 4).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.

2.3.1 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 4.

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.

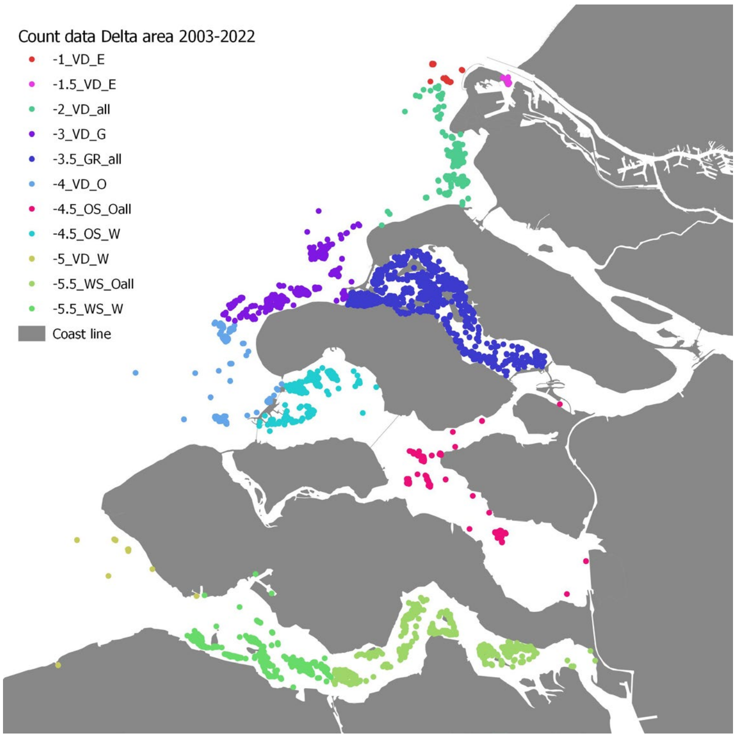


Figure 4. GPS location of the survey plane with seal sightings recorded during monitoring of 2003-2021 (data DMP). Different colours represent the different sub regions used in this report.

2.3.2 Analysis

GAM models were fitted to best describe the observed variations in counts prior to the onset of piledriving 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.

2.4 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 5.

Table 5. 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 piledriving 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.

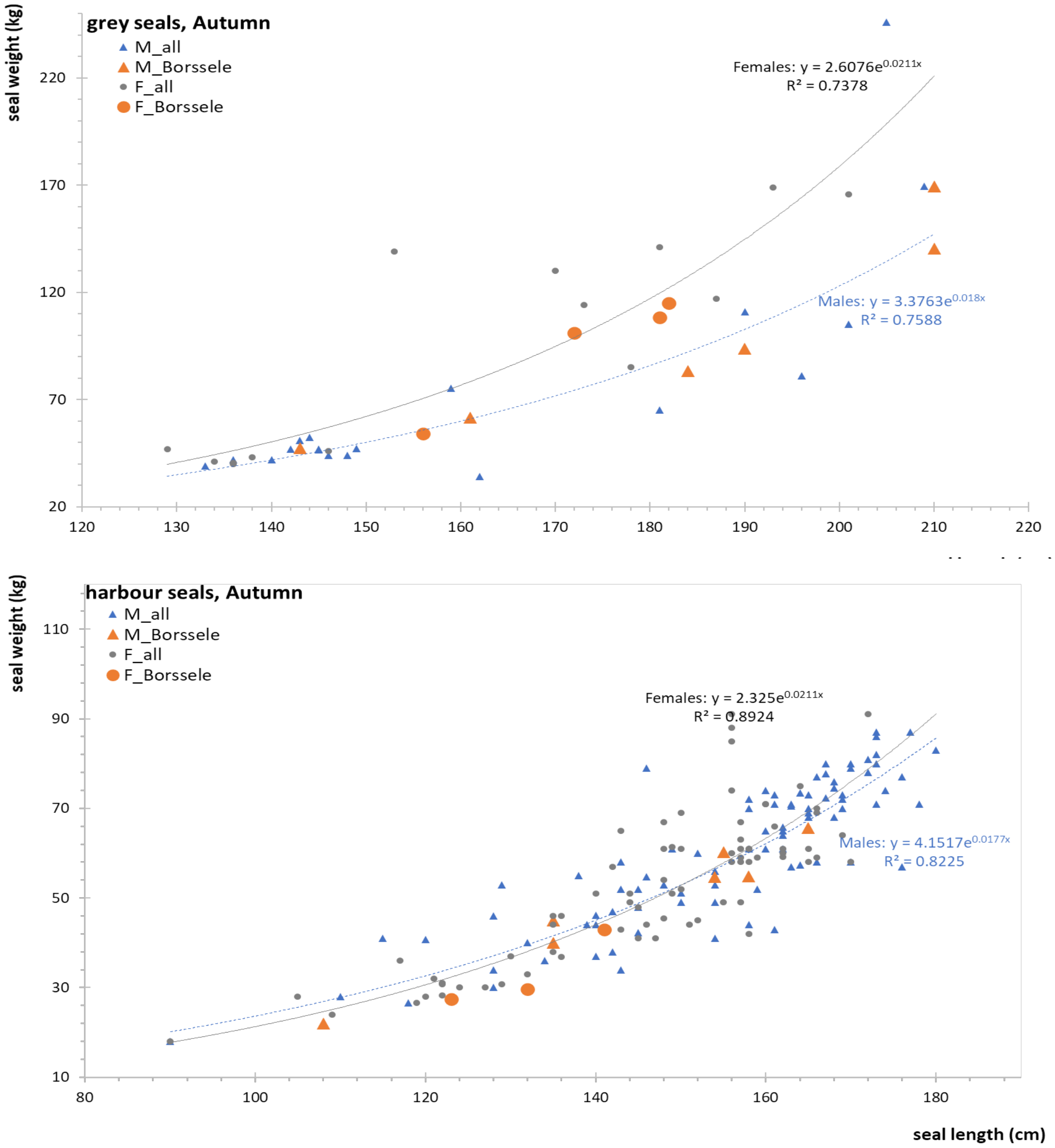


Figure 5. Length and weight of seals captured in September 2019, compared to all seals captured in autumn 1990-2017. Top grey seals, bottom harbour seals. Orange markers indicate tracked animals. An exponential function was used to capture the (non-linear) relationship between seal length and weight.

Compared to an exponential relationship of length and weight based on all seals weighed (see Figure 5), 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

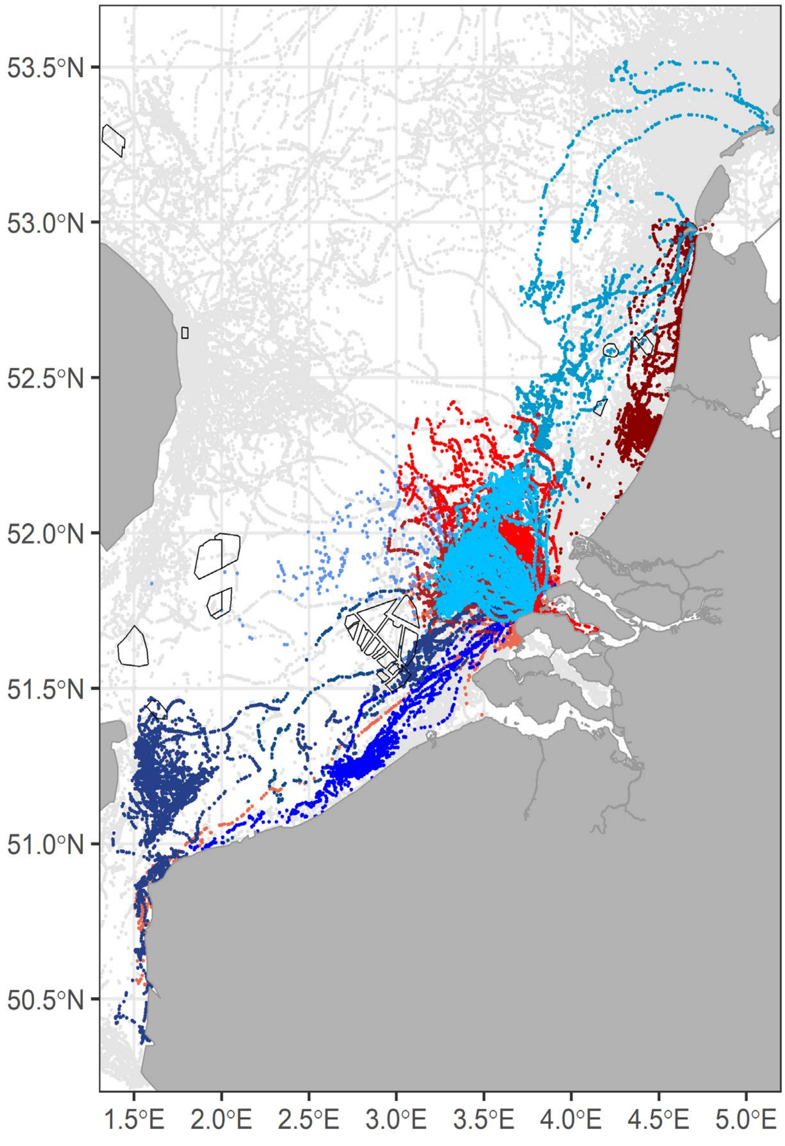
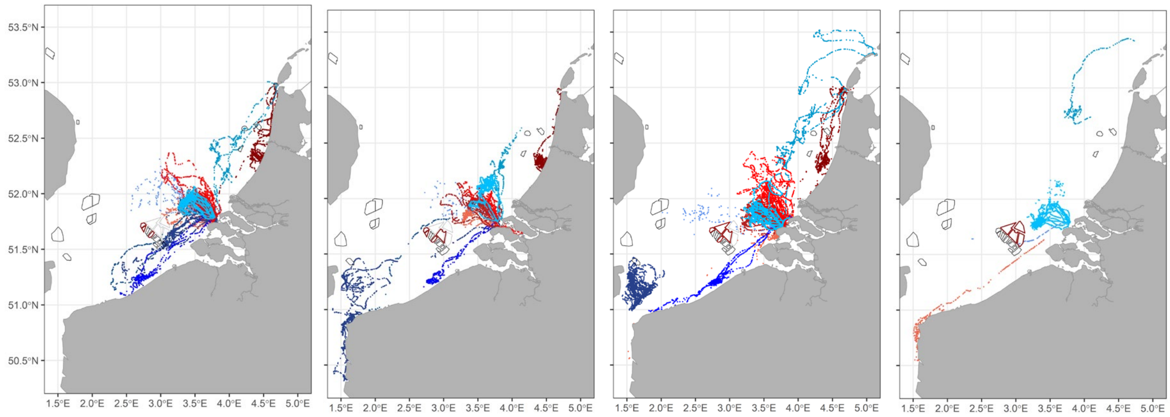


Figure 6. Movements of 10 tracked grey seals sept 2019-mar 2020. Red tones: females; blue tones: males; light grey: tracks of previous projects

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 6). 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 7 depicts the movements of grey seals during these four different periods of piledriving. 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
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 7. Movements of 10 tracked grey seals sept 2019-mar 2020. In the course of different piledriving regimes. 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 8). 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 piledriving are depicted in Figure 9.

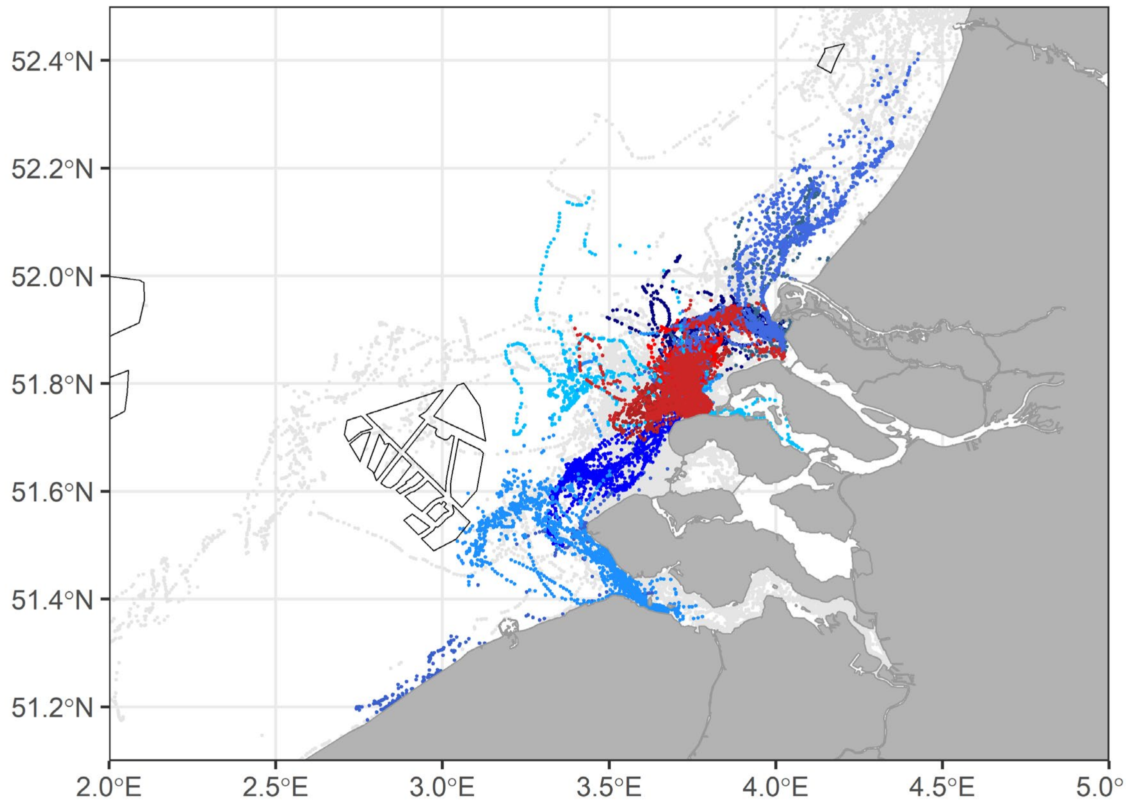
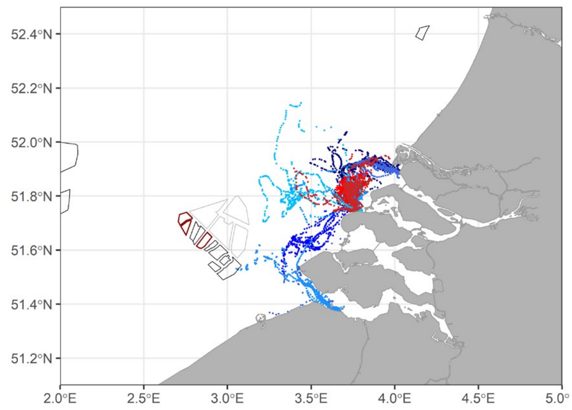
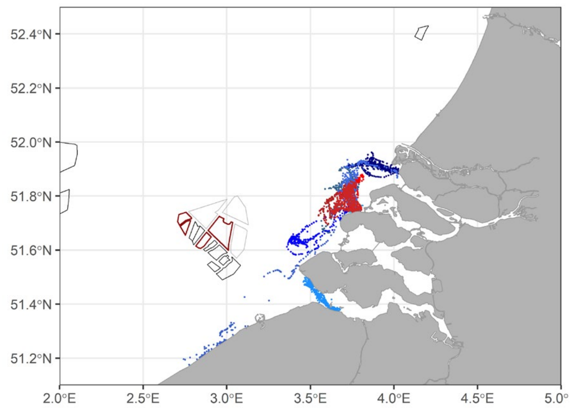


Figure 8. Movements of 10 tracked harbour seals sept 2019-mar 2020. Red tones: females; blue tones: males; light grey: tracks of previous projects

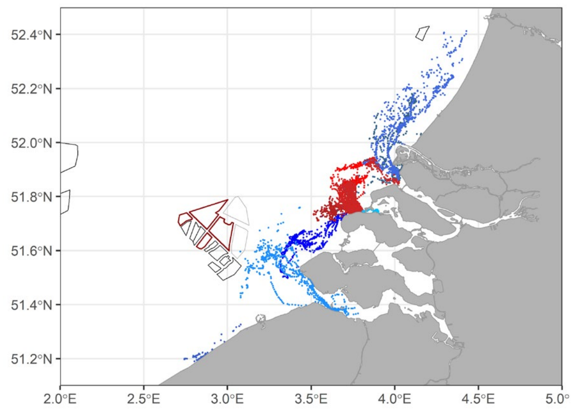
During the first period all trackers were functioning, however, in the course of the second period one tracker was lost and three others during the third period. During the fourth period all other six stopped functioning by February 8th 2022.



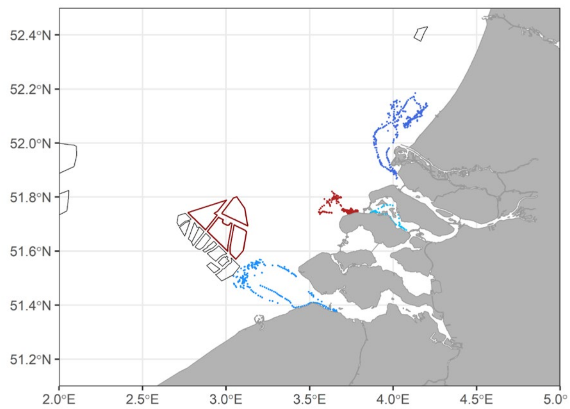
8 Sept.-19 Oct. 2019 *Seamade & Northwester pile driving*



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 9. Movements of 10 tracked harbour seals sept 2019-mar 2020. 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 piledriving

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.

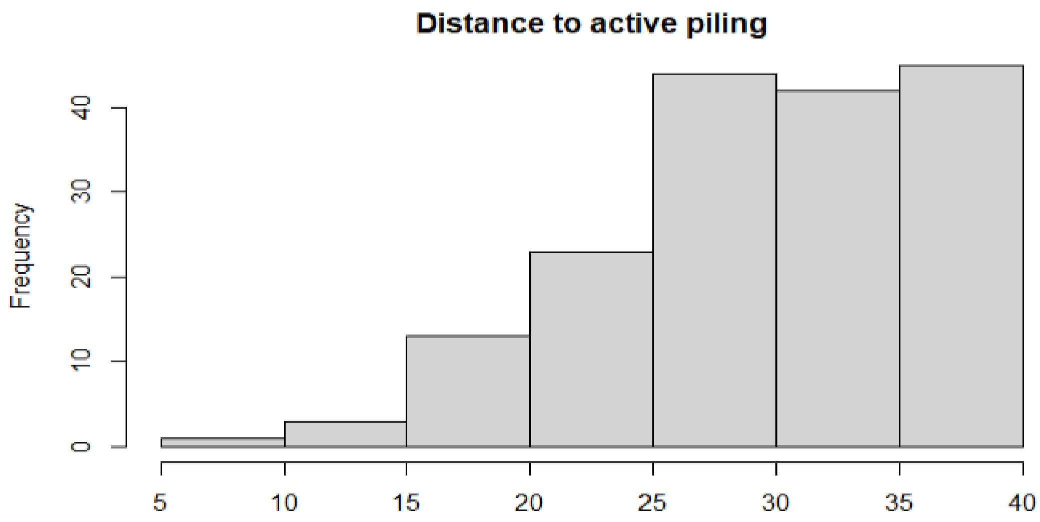


Figure 10. Frequency distribution of the number of events where GPS tracked seals were within a specific distance (in km) to a pile driving events

For each exposure (i.e., at the onset of pile-driving, the seal was within 35km), 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 large decline in vertical speed (Figure 11).

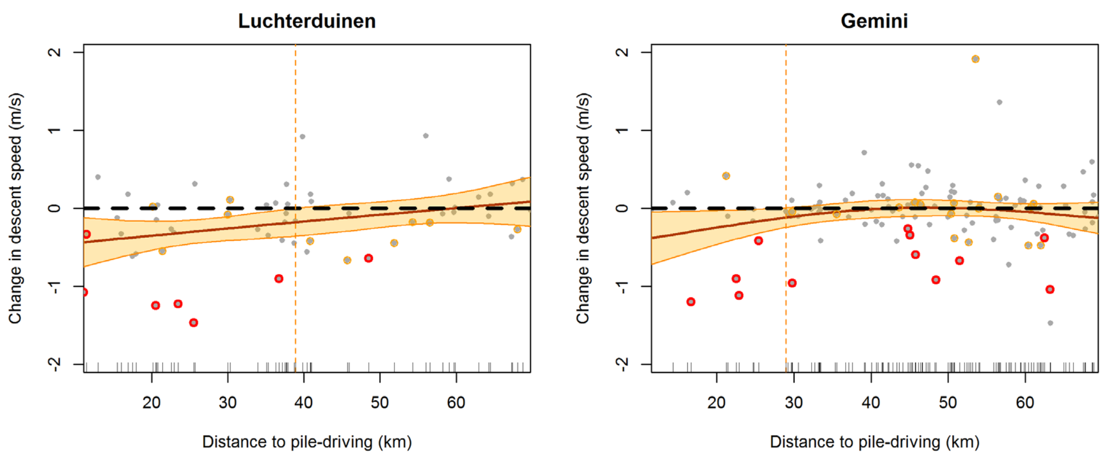


Figure 11. Change in descent speed (m/s) during pile-driving for Luchterduinen (left) and Gemini (right), as function of distance to the pile-driving. Each grey point represents an exposure. The solid red line represents the mean estimate, and the shaded orange area the 95% confidence interval (with 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 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 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 12shows the change in descent speed as function of distance the Borssele 1, 2, 3 & 4, Sea Made and North Western construction site.

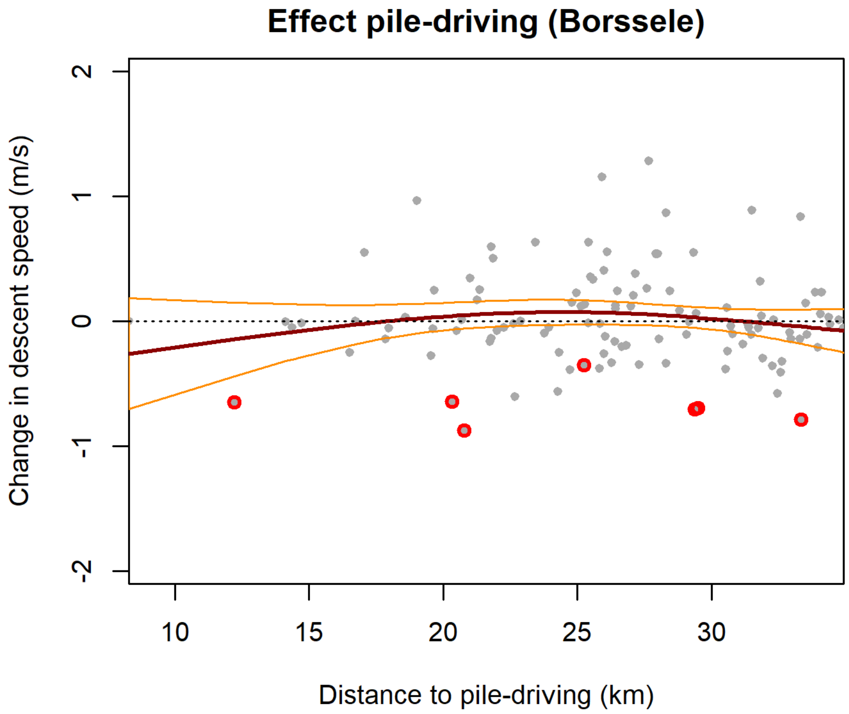


Figure 12. Change in descent speed (m/s) during pile-driving for Borssele as function of distance to the pile-driving. See Figure 11 for more details

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. We will now inspect some exposures 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, we expect the seal to have already detected the ongoing construction and responded prior to pile-driving.

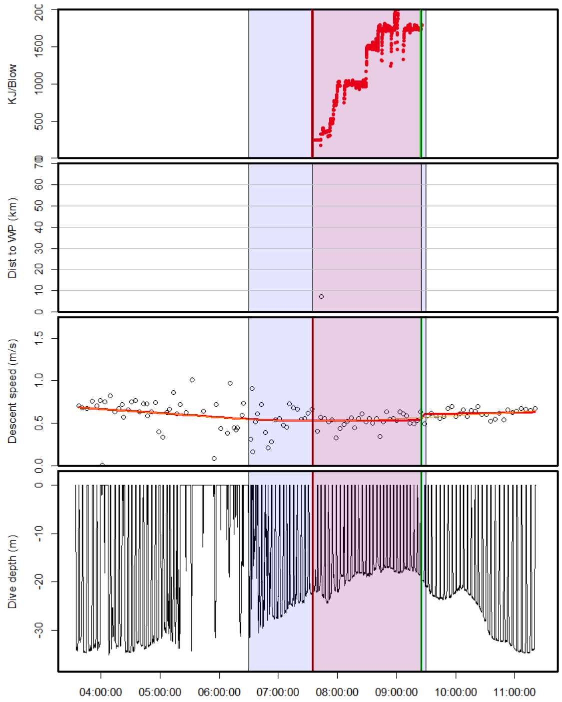


Figure 13. The diving behaviour prior, during and after pile-driving for harbour seal pv69-138-19, 8.3 km from the construction site on 2019-12-26. The top panel shows the blow intensity (y-axis, in kJ) as function of time (x-axis). The blue transparent area is the period when the ADD was turned on. 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 14). 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 minute safter pile-driving had ceased, the descent speed returned back to pre-piling levels

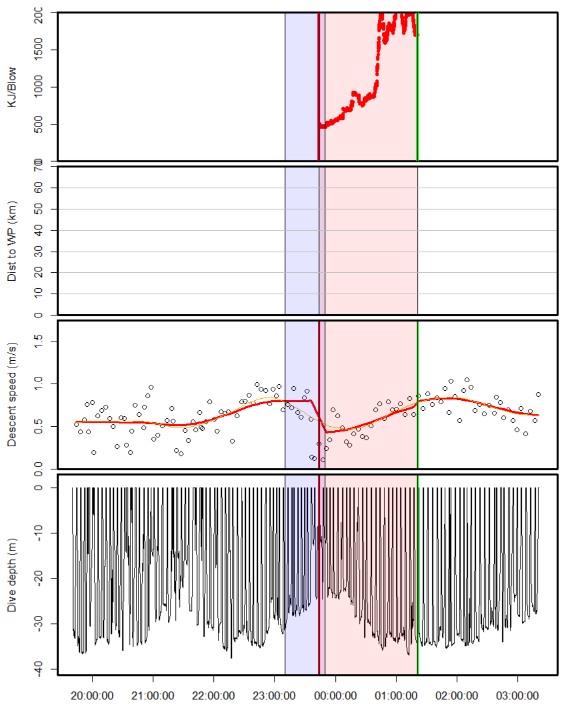


Figure 14 The diving behaviour prior, during and after pile-driving for grey seal hg69-158-19, 12.2 km from the construction site on the night from 16 to 17 December 2019

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 15.That seal that did not show a sudden change in descent speed after pile-driving started (hence no significant change in Figure 15), 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.

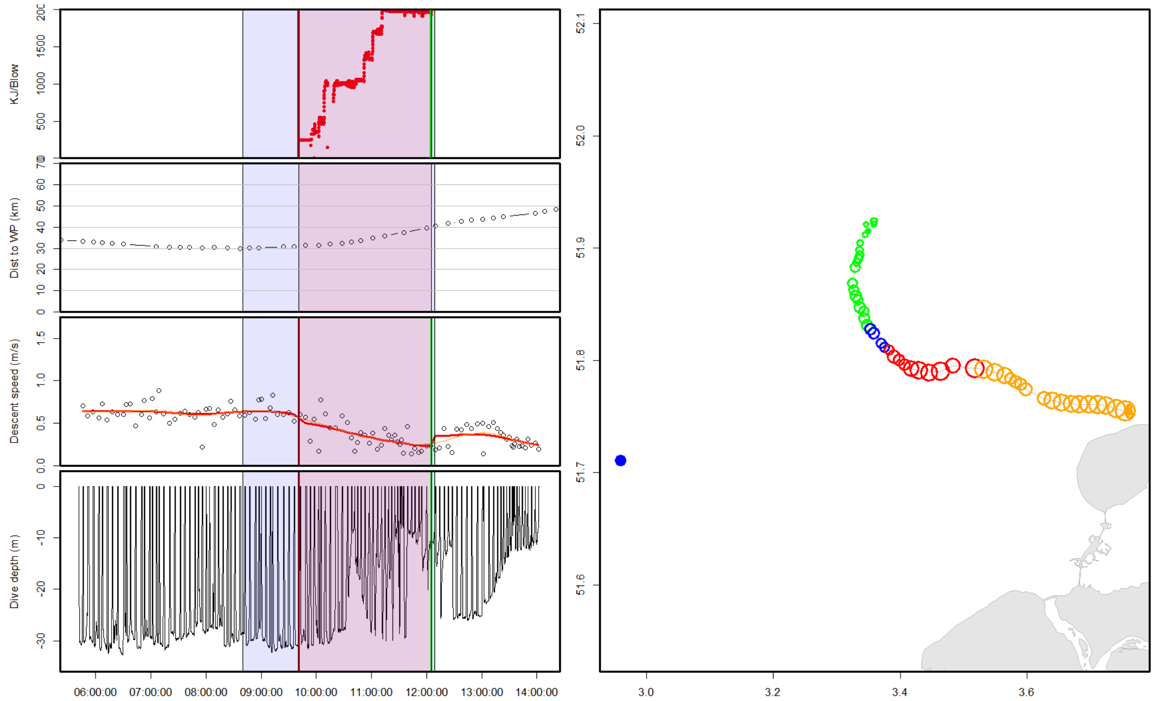


Figure 15 The behaviour for grey seal hg69-158-19, 14.4 km from the construction site on 25 December 2019. The right panel shows the movement of the seal during four different periods, namely the period prior to ADD and pile-driving (green), during ADD (blue), during pile-driving (red) and after pile-driving (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 15. 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 17. 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).

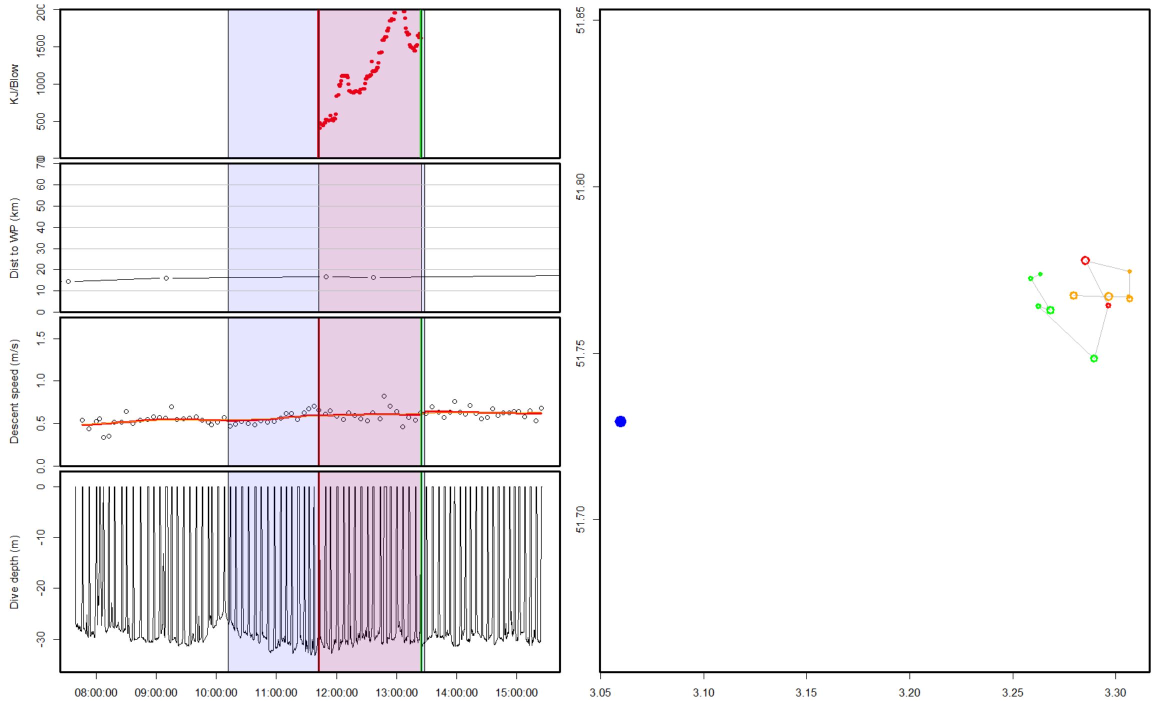


Figure 16 The behaviour of grey seal hg69-159-19, 15 km from the construction site on 8 January 2020. No clear change in diving behaviour or movement is apparent. However, descent speed is

already reasonably low prior to pile-driving, and the seal might already be in transit mode prior to pile-driving.

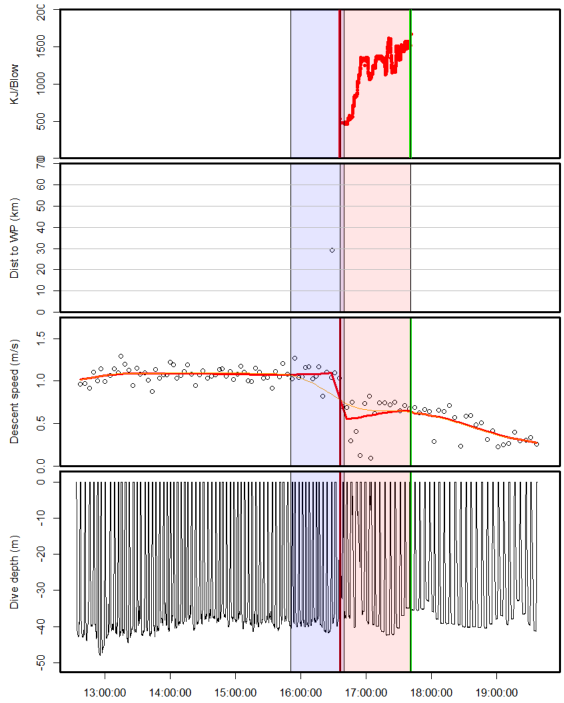
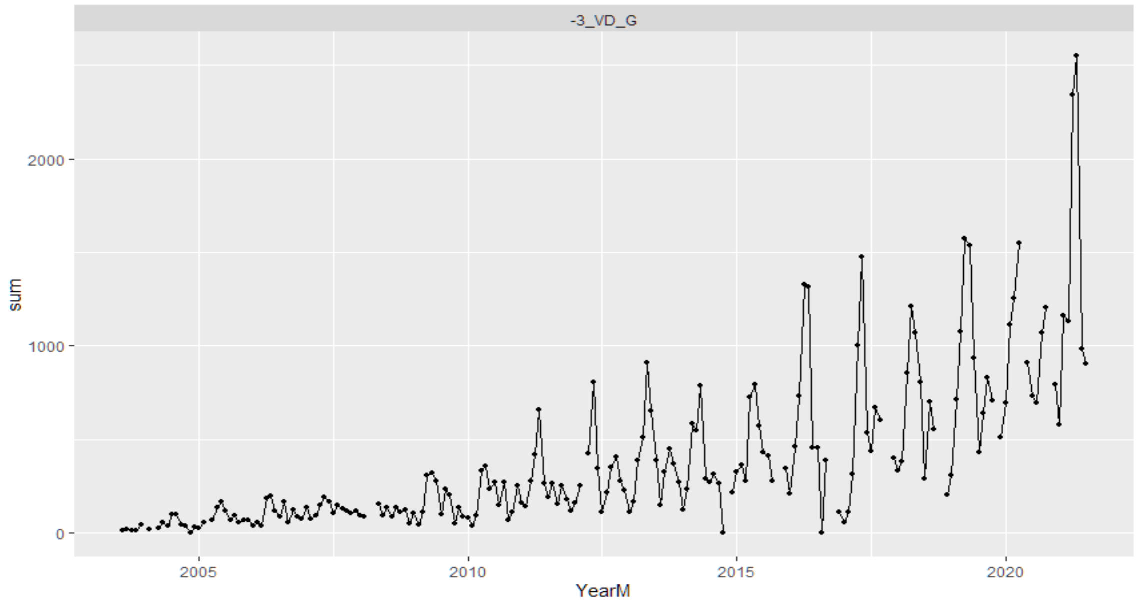


Figure 17 The behaviour for grey seal hg69-158-19, 29.4 km from the construction site (P81) on 28 November 2019. That seal is residing in relative deep water (40m) and showing a high vertical descent speed (>1 m/s) prior to pile driving. Immediately after the commencement of pile driving, a sudden drop in descent speed is apparent.

3.1 Surveys

3.1.1 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 4 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 18).



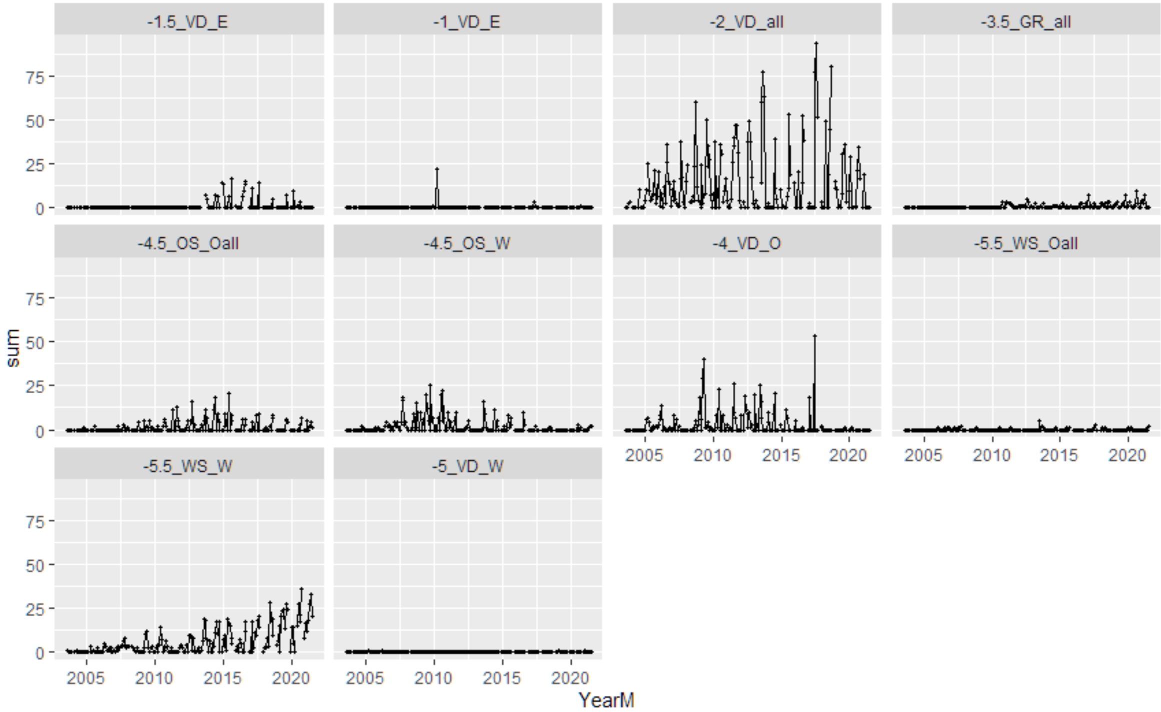


Figure 18. Count results for grey seals in the different sub areas of the Delta, see Figure 4 for locations. Note the different scale of sub area -3_VD_G.

Table 6. 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 piledriving commenced are often higher than predicted, though also here numbers are low (Figure 19).

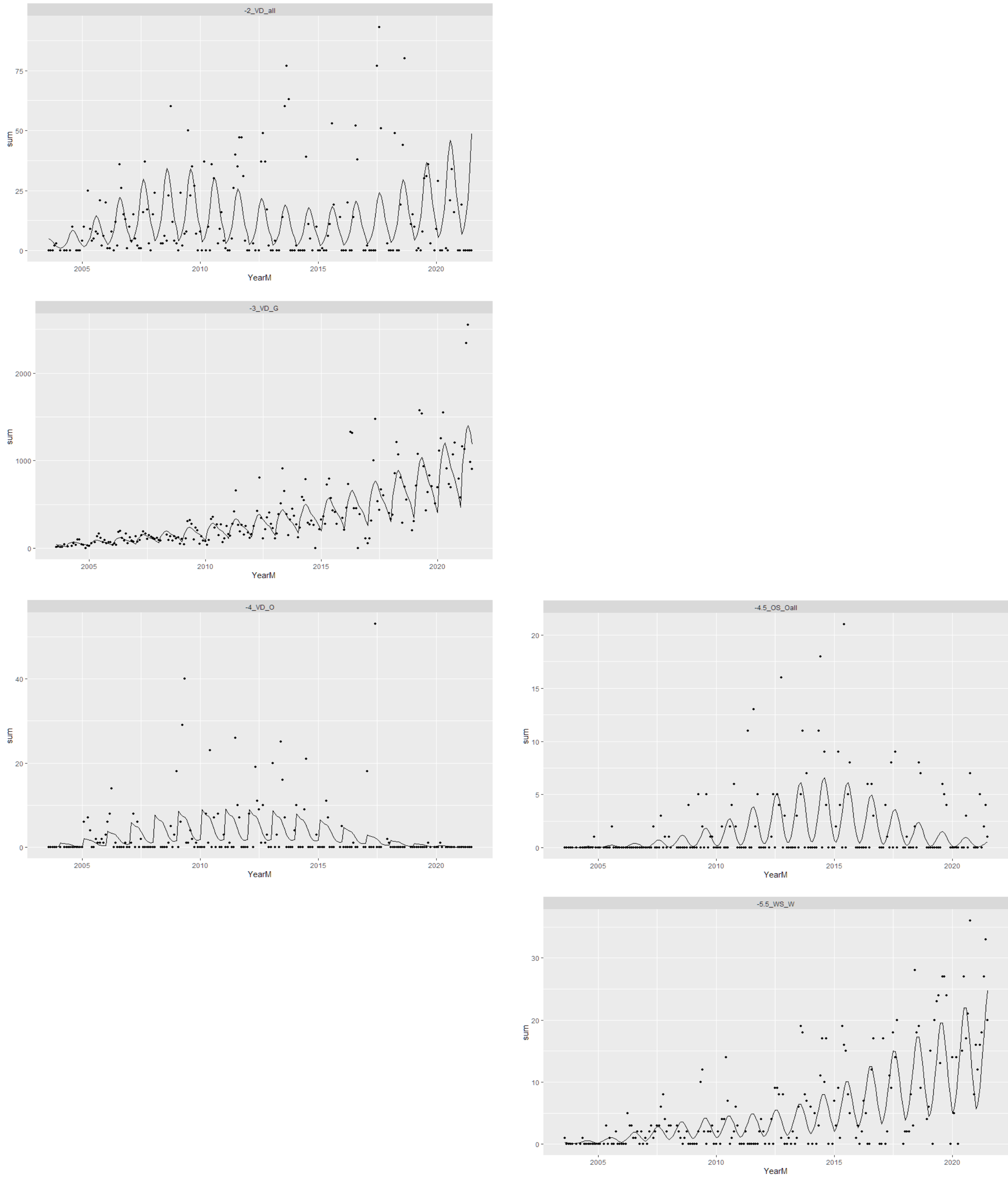


Figure 19. Predicted counts (line) and actual survey results (dots) for grey seals in different sub areas of the Delta. Locations are arranged from north to south, left column represent sub areas in the Voordelta, right column sites in land (-4.5 is the Oosterschelde, -5.5 the Westerschelde).

3.1.2 Harbour seals

Compared to the grey seals, harbour seals are more distributed throughout the different sub areas in the Delta (Figure 20; see Figure 4 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).

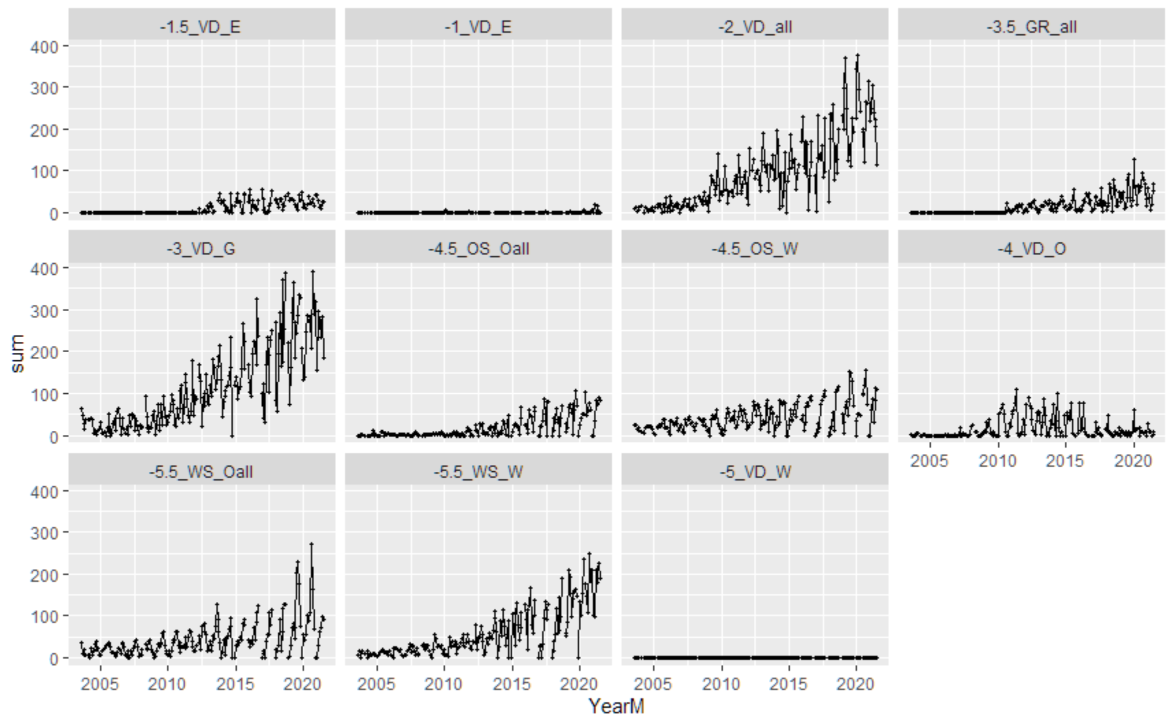


Figure 20. Count results for harbour seals in the different sub areas of the Delta, see Figure 3 for locations.

Table 7. 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).

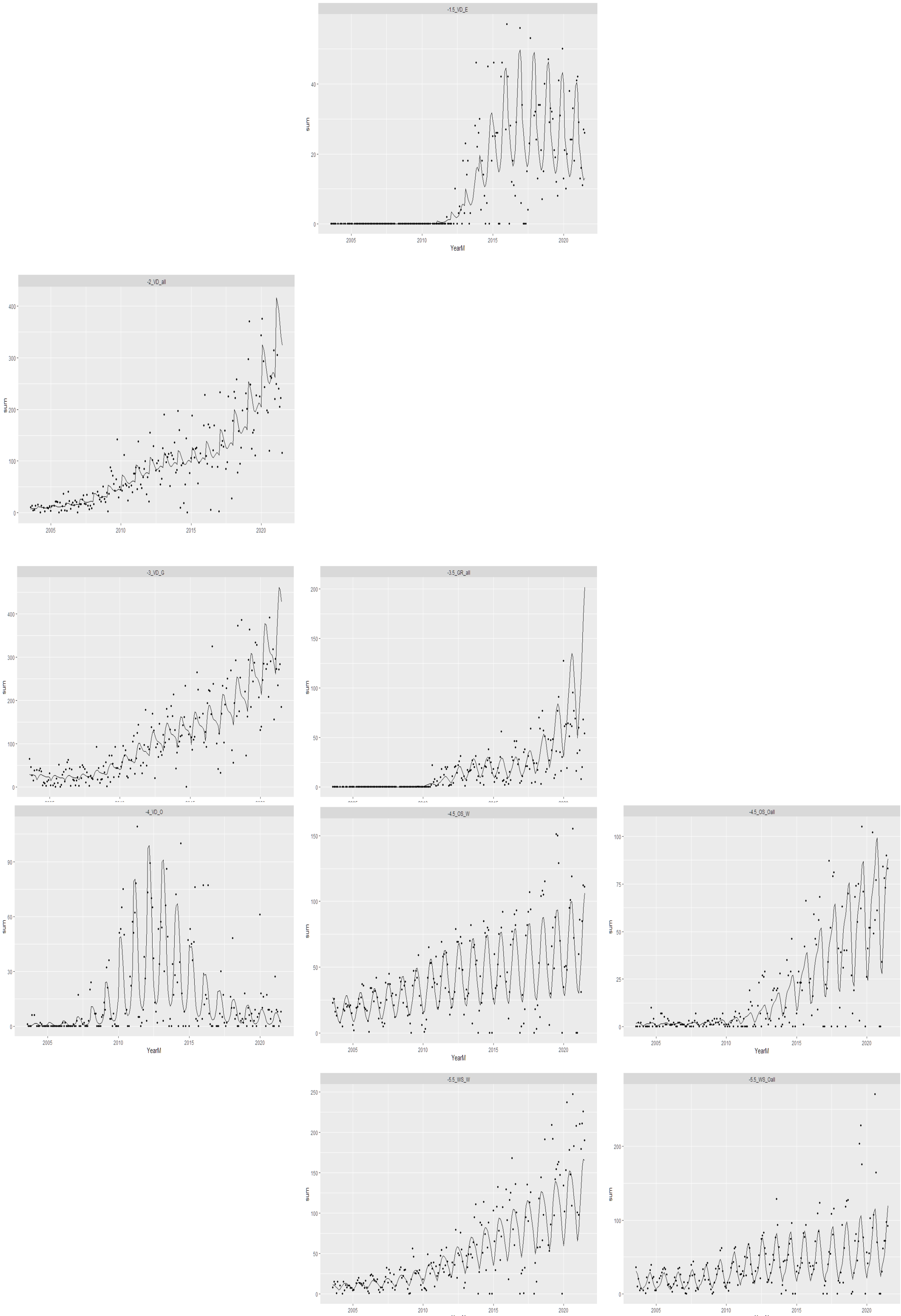


Figure 21. Predicted counts (line) and actual survey results (dots) for harbour seals in different sub areas of the Delta. Locations are arranged from north to south, left column represent sub areas in the Voordelta, right column sites in land (-1.5 is near Rotterdam Harbour, -3.5 is the Grevelingen, -4.5 is the Oosterschelde, -5.5 the Westerschelde).

Results, like for the grey seals, differed between the sub areas (Figure 21). In the north of the Voordelta (-2_VD_all and -3_VD_G), counted numbers after piledriving 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. The harbour seal numbers in the Oosterschelde (-4.5_OS..) and even more so in the Westerschelde (-5.5_WS..) are higher than expected after pile driving commenced. 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.

3.2 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 22. depicts the annual number of seals found dead along the Delta coasts.

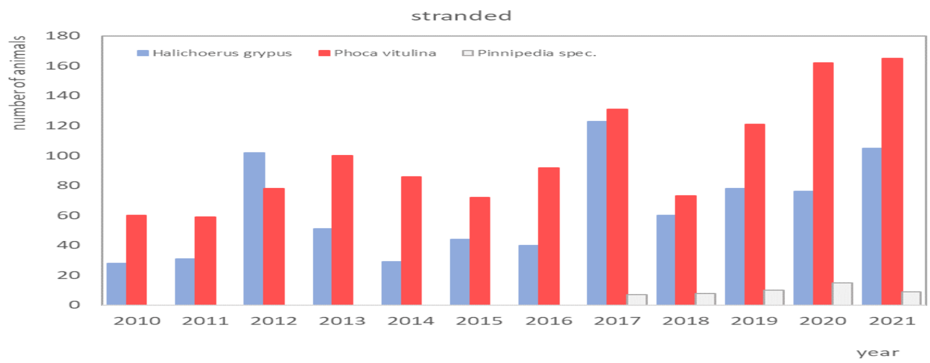
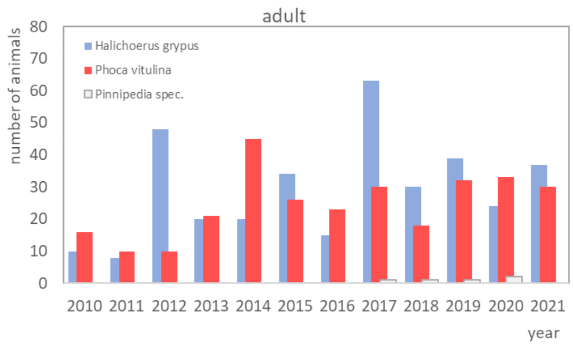
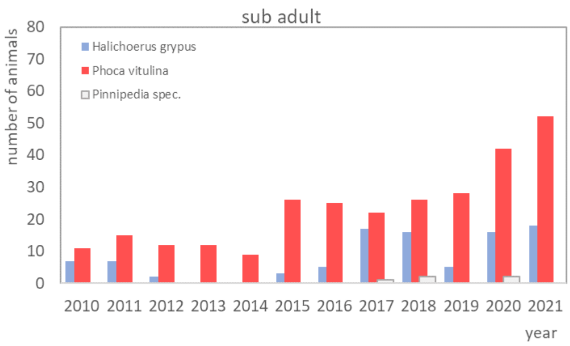


Figure 22. Annual numbers of seals found dead along the coasts of the Dutch Delta 2010-2021.

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 piledriving 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.





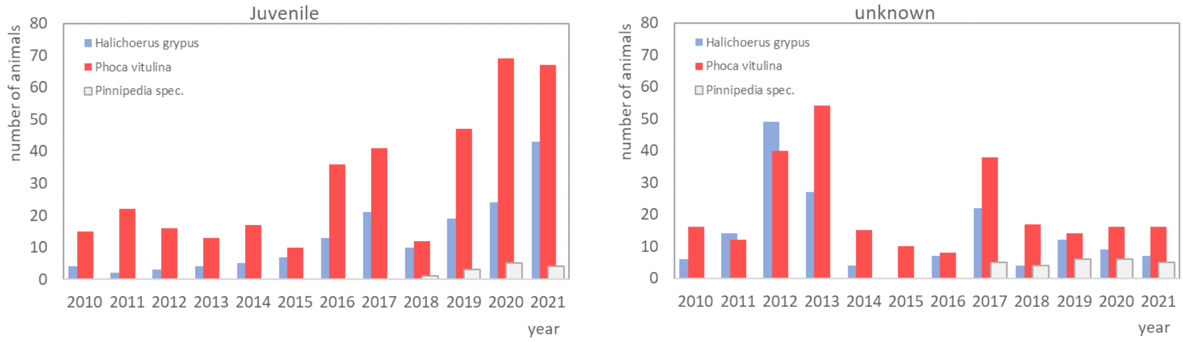
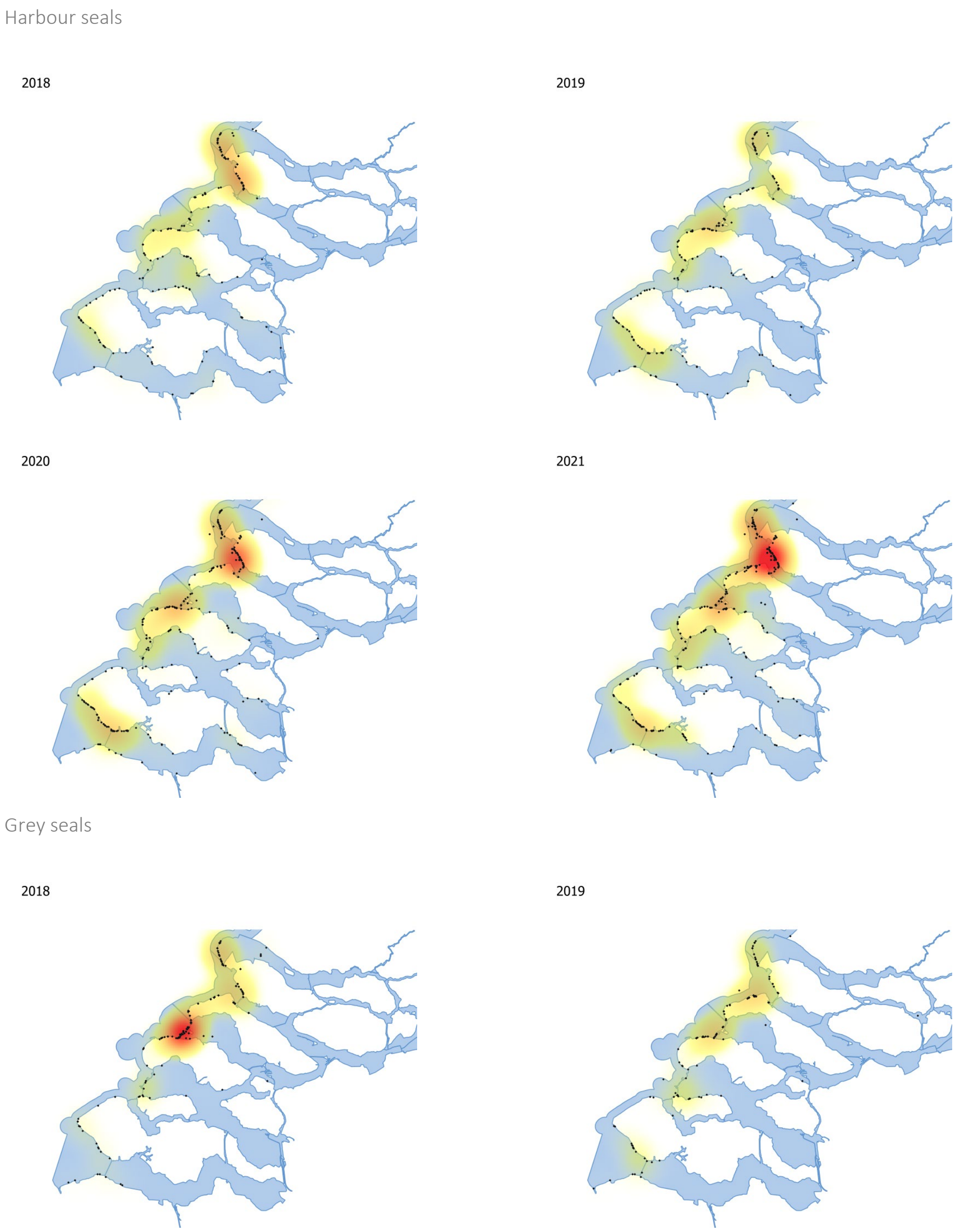


Figure 23. Annual numbers of seals found dead discerned by age classes.

When seals die, the current might influence where the animals strand. In Figure 24 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.



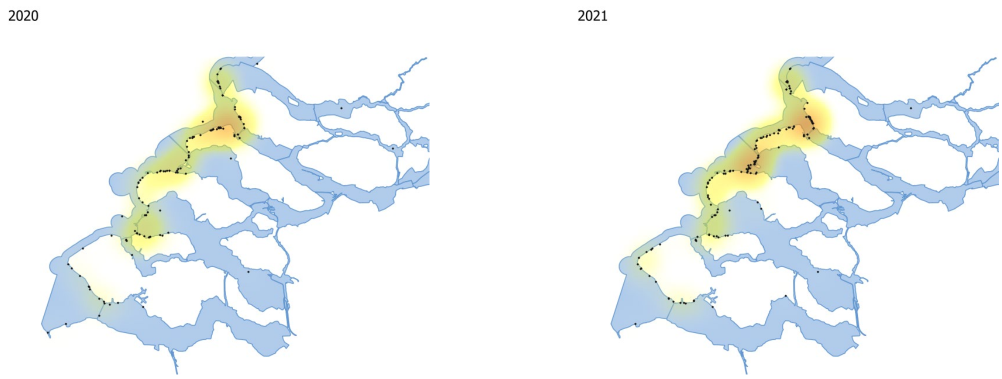


Figure 24. Distribution of dead stranded harbour (top) and grey seals (bottom) in the Delta area 2018-2021. Concentration is indicated with so called heatmaps, individual finding locations are indicated with a black dot.

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 way of testing the effect of piledriving on the animals 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 6 and Figure 8), 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 7 and Figure 9). 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 *13*). This seal (and other seals) might have been even closer to the pile-driving site, but there are often gaps in GPS location fixes. This seems to occur more often during pile driving events, possibly because seals flee, being less frequently at the surface or surfacing differently. This has been observed in previous studies, but not

properly tested. This harbour seal 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, in average an hour before piling (Table 4), the descent speed further declined, suggesting the seal would not dive straight to the bottom but engage 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. As these changes do not coincide exactly with the times of onset of piledriving or ADD, it is not certain that these are caused by the pile-driving.

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 at which seals are affected by the piledriving operations. There are several possible explanations for these.

1. Assuming the mitigation measures reduced the sound exposure levels (SEL) (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. Typically, densities of seals at sea would be around 1-2 individuals per km^2.
2. Compared to GEMINI for example, the construction site is, relatively close to shore, in the east side of the assumed impact area waters are shallow, thus lower or at least attenuated SEL are expected on the east side of the wind farm area.
3. The region around the Voordelta is one of the most intensive shipping areas in the North Sea, moreover the construction of the Borssele windfarms was not the only activity in the region. As explained, at least two other windfarms were piledriving simultaneously and other parks were being finalised or started. Also, other offshore wind parks were constructed well before this study, e.g., Thornton Bank was already constructed in 2007 and construction was almost ongoing since then. The seals in the area might have habituated to the ambient human noise levels present or adapted their behaviour. 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 tracked for this study) were not naïf to the situation and might also not represent all seals using the Delta area normally. As piledriving was ongoing prior to the tracking we could assume seals might have left the area. This has been observed for seals (Edrén *et al.*, 2010) and in porpoises, 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 8 & Figure 9). Potentially a more in depth study would help identify differences between the tracked animals. At the moment we can only speculate about the cause, but in our view, 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 piledriving 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 where as 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. For example more dead juvenile grey seals are found in the area than are counted during breeding. It should be noted however that the maximum numbers counted in the area have grown. A more detailed study on how the number of animals found dead relate to the number observed.

5 Conclusions and recommendations

Unintentionally, this study on the influence of piledriving of wind mills at sea on seal behaviour and distribution was somewhat impaired by pile driving and construction of windfarms or other human activities. Also the sound was mitigated, potentially dampening the magnitude of effect. This impeded this study to result in clear conclusions, either demonstrating the lack of effects or on the contrary, proving them.

The harbour and grey seals weighed during tracking 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 piledriving 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, depending on the sub area and species. And finally, more dead seals were found following the pile driving period.

Observed changes in this study could be the direct or indirect result of the piledriving 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. Recurringly 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.

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 25). 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 available to 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.

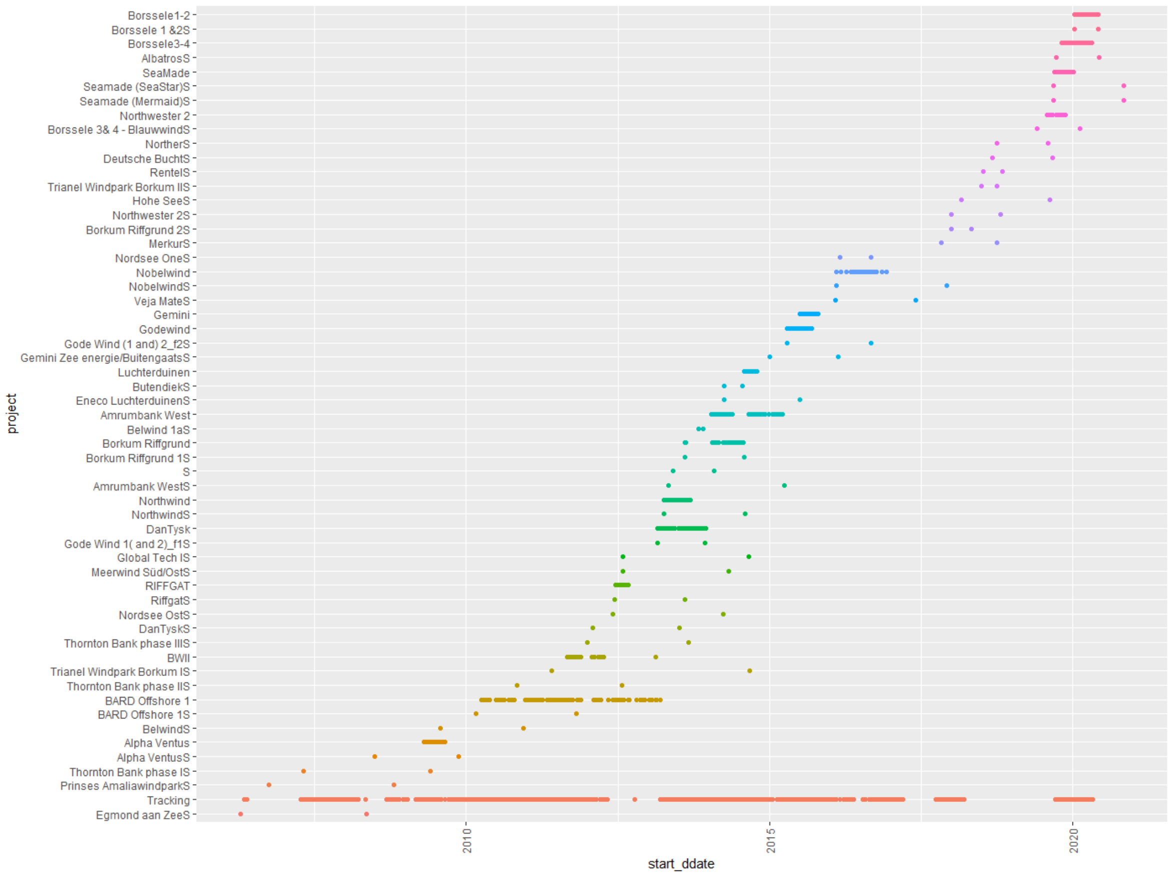


Figure 25 Timeline of construction of windfarms in the Southern North Sea compared to the seal tracking data of WMR (orange line below). Start and end of the consturuction is indicated by a dot, piledriving by a line (when data is available). Every line represents one windfarm (project). On the x-axis 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 above.

5.2 Recommendations

- It will be necessary to study the effect of the intended large scale changes to the marine environment.
- Future studies should include long term data, allowing to take account of processes that might influence long living organisms or cause changes on a higher level (population or ecosystem) than the instantaneous reaction of a single individual.
- Comparable to the ecological monitoring schemes, authorities responsible for permitting activities at sea should create public records of where when and how to facilitate the study of possible effects of these activities, also in hindsight.

For studies of seals, especially as an indicator for the changes in the marine environment

- monitoring should be continued, and detailed analysis should be done to better understand population changes
- more detailed stranding data should be better recorded and at least a subsample of the seals stranded should be necropsied. 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, 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.

References

Aarts, G., Benda-Beckmann, V., Lucke, K., Sertlek, H., Van Bemmelen, R., Geelhoed, S., Brasseur, S., Scheidat, M., Lam, F., Slabbekoorn, H., 2016a. Harbour porpoise movement strategy affects cumulative number of animals acoustically exposed to underwater explosions. Marine Ecology Progress Series 557, 261-275.

Aarts, G., Brasseur, S., Kirkwood, R., 2018a. Behavioural response of grey seals to pile-driving, Wageningen Marine Research.

Aarts, G., Brasseur, S., Kirkwood, R., 2018b. Behavioural response of grey seals to pile-driving, C006/18 Wageningen Marine Research, Den Helder.

Aarts, G., Cremer, J., Kirkwood, R., Wal, J.T.v.d., Matthiopoulos, J., Brasseur, S., 2016b. Spatial distribution and habitat preference of harbour seals (Phoca vitulina) in the Dutch North Sea, Wageningen Marine Research, Den Helder :.

Ashley, E.A., Olson, J.K., Adler, T.E., Raverty, S., Anderson, E.M., Jeffries, S., Gaydos, J.K., 2020. Causes of Mortality in a Harbor Seal (Phoca vitulina) Population at Equilibrium. Frontiers in Marine Science 7.

Bellmann M. A., B.J., May A., Wendt T., Gerlach S. & Remmers P., 2020. Underwater noise during percussive pile driving: Influencing factors on pile-driving noise and technical possibilities to comply with noise mitigation values ERa Report Supported by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit (BMU)), FKZ UM16 881500. Commissioned and managed by the Federal Maritime and Hydrographic Agency (Bundesamt für Seeschifffahrt und Hydrographie (BSH)), Order No. 10036866. Edited by the itap GmbH Oldenburg.

Boehlert, G.W., Gill, A.B., 2010. Environmental and ecological effects of ocean renewable energy development. A Current Synthesis. Oceanography 23, 68-81.

Brasseur, S., Creuwels, J., van der Werf, B., Reijnders, P., 1996. Deprivation indicates necessity for haul-out in harbor seals. Marine Mammal Science 12, 619-624.

Brasseur, S., Kirkwood, R., Aarts, G., 2016. Monitoring and Evaluation Program (MEP) for seals during Luchterduinen windfarm operation. Tender document 16.43034.

Brasseur, S., Kirkwood, R., Aarts, G., 2018a. Seal monitoring and evaluation for the Gemini offshore windfarm: Tconstruction - 2015 report, Wageningen Marine Research, Yerseke.

Brasseur, S., Schop, J., Cremer, J., Aarts, G., 2018b. Harbour seal monitoring and evaluation for the Luchterduinen offshore windfarm : Final report, Wageningen Marine Research, Texel.

Brasseur, S., Schop, J., Cremer, J., Aarts, G., 2018c. Harbour seal monitoring and evaluation for the Luchterduinen offshore windfarm: final report, Wageningen Marine Research, Texel.

Brasseur, S.M.J.M., 2017. Seals in motion : how movements drive population development of harbour seals and grey seals in the North Sea. , Wageningen University https://doi.org/10.18174/418009.

Brasseur, S.M.J.M., Reijnders, P.J.H., Cremer, J., Meesters, E., Kirkwood, R., Jensen, L.F., Jeβ, A., Galatius, A., Teilmann, J., Aarts, G., 2018d. Echoes from the past: Regional variations in recovery within a harbour seal population. PLOS ONE 13, e0189674.

Brasseur, S.M.J.M., van Polanen Petel, T.D., Gerrodette, T., Meesters, E.H.W.G., Reijnders, P.J.H., Aarts, G., 2015. Rapid recovery of Dutch gray seal colonies fueled by immigration. Marine Mammal Science 31, 405-426.

Cunningham, K.A., Reichmuth, C., 2016. High-frequency hearing in seals and sea lions. Hearing Research 331, 83-91.

Edrén, S.M.C., Andersen, S.M., Teilmann, J., Carstensen, J., Harders, P.B., Dietz, R., Miller, L.A., 2010. The effect of a large Danish offshore wind farm on harbor and gray seal haul-out behavior. Marine Mammal Science 26, 614-634.

Galatius, A., Engbo, S.G., Teilmann, J., Beest, F.M.v., 2021. Using environmental variation to optimize aerial surveys of harbour seals. ICES Journal of Marine Science 78, 1500-1507.

Hastie, G., Merchant, N.D., Götz, T., Russell, D.J.F., Thompson, P., Janik, V.M., 2019. Effects of impulsive noise on marine mammals: investigating range-dependent risk. Ecological Applications 29.

Hastie, G.D., Russell, D.J.F., McConnell, B., Moss, S., Thompson, D., Janik, V.M., 2015. Sound exposure in harbour seals during the installation of an offshore wind farm: predictions of auditory damage. Journal of Applied Ecology 52, 631-640.

Hoekstein, M.S.J., Sluijter, M., van Straalen, K.D., 2022. Watervogels en zeezoogdieren in de Zoute Delta 2020/2021. .

Inger, R., Attrill, M.J., Bearhop, S., Broderick, A.C., Grecian, W.J., Hodgson, D.J., Mills, C., Sheehan, E., Votier, S.C., Witt, M.J., Godley, B.J., 2009. Marine Renewable Energy: Potential Benefits to Biodiversity? An Urgent Call for Research. Journal of Applied Ecology 46, 1145-1153.

Joy, R., Wood, J.D., Sparling, C.E., Tollit, D.J., Copping, A.E., McConnell, B.J., 2018. Empirical measures of harbor seal behavior and avoidance of an operational tidal turbine. Marine Pollution Bulletin 136, 92-106.

Kastelein, R., Helder-Hoek, L., Gransier, R., Terhune, J., Jennings, N., de Jong, C.F., 2015. Hearing thresholds of harbor seals (Phoca vitulina) for playbacks of seal scarer signals, and effects of the signals on behavior. Hydrobiologia 756, 75-88.

Kastelein, R.A., Helder-Hoek, L., Kommeren, A., Covi, J., Gransier, R., 2018a. Effect of pile-driving sounds on harbor seal (Phoca vitulina) hearing. The Journal of the Acoustical Society of America 143, 3583-3594.

Kastelein, R.A., Helder-Hoek, L., Terhune, J.M., 2018b. Hearing thresholds, for underwater sounds, of harbor seals (Phoca vitulina) at the water surface. The Journal of the Acoustical Society of America 143, 2554-2563.

Kastelein, R.A., Hoek, L., Gransier, R., Jennings, N., 2013. Hearing thresholds of two harbor seals (*Phoca vitulina*) for playbacks of multiple pile driving strike sounds. Journal of the Acoustical Society of America 134, 2307-2312.

Kauhala, K., Korpinen, S., Lehtiniemi, M., Raitaniemi, J., 2019. Reproductive rate of a top predator, the grey seal, as an indicator of the changes in the Baltic food web. Ecological Indicators 102, 693-703.

Keen, K.A., Beltran, R.S., Pirotta, E., Costa, D.P., 2021. Emerging themes in Population Consequences of Disturbance models. Proceedings of the Royal Society B: Biological Sciences 288, 20210325.

Kirkwood, R., Aarts, G.M.D.I., Brasseur, S.M.J.M., 2015. Seal monitoring and evaluation for the Luchterduinen offshore wind farm: 2. Tconstruction - 2014 report, IMARES Wageningen UR, IJmuiden.

Kirkwood, R., Bos, O., Brasseur, S.M.J.M., 2014. Seal monitoring and evaluation for the Luchterduinen offshore wind farm 1. T0-2013 report, IMARES Wageningen UR, IJmuiden.

Kirkwood, R.J., Aarts, G.M., Brasseur, S.M.J.M., 2016. Seal monitoring and evaluation for the Luchterduinen offshore wind farm: 3. T1 – 2015 report, WMR, Den Helder, p. 83.

Kunc, H.P., McLaughlin, K.E., Schmidt, R., 2016. Aquatic noise pollution: implications for individuals, populations, and ecosystems. Proceedings of the Royal Society B: Biological Sciences 283, 20160839.

Lucke, K., Hastie, G.D., Ternes, K., McConnell, B., Moss, S., Russell, D.J.F., Weber, H., Janik, V.M., 2016. Aerial low-frequency hearing in captive and free-ranging harbour seals (*Phoca vitulina*) measured using auditory brainstem responses. Journal of Comparative Physiology A 202, 859-868.

Meesters, E., Reijnders, P., Brasseur, S., Tougaard, S., Stede, M., Siebert, U., Härkönen, T., 2009. An effective survey design for harbour seals in the Wadden Sea: tuning Trilateral Seal Agreement and EU□ Habitat Directive requirements. Abstract, 12th International Scientific Wadden Sea Symposium.

Ramasco, V., Biuw, M., Nilssen, K.T., 2014. Improving time budget estimates through the behavioural interpretation of dive bouts in harbour seals. Animal Behaviour 94, 117-134.

Reichmuth, C., Holt, M.M., Mulsow, J., Sills, J.M., Southall, B.L., 2013. Comparative assessment of amphibious hearing in pinnipeds. Journal of Comparative Physiology A 199, 491-507.

Ruser, A., Dähne, M., Sundermeyer, J., Lucke, K., Houser, D.S., Finneran, J.J., Driver, J., Pawliczka, I., Rosenberger, T., Siebert, U., 2014. In-air evoked potential audiometry of grey seals (Halichoerus grypus) from the North and Baltic Seas. PloS one 9, e90824-e90824.

Russell, D.J., Hastie, G.D., Thompson, D., Janik, V.M., Hammond, P.S., Scott-Hayward, L.A., Matthiopoulos, J., Jones, E.L., McConnell, B.J., 2016. Avoidance of wind farms by harbour seals is limited to pile driving activities. Journal of Applied Ecology 53, 1642-1652.

Sigourney, D.B., Murray, K.T., Gilbert, J.R., Ver Hoef, J.M., Josephson, E., DiGiovanni Jr., R.A., 2022. Application of a Bayesian hierarchical model to estimate trends in Atlantic harbor seal (Phoca vitulina vitulina) abundance in Maine, U.S.A., 1993–2018. Marine Mammal Science 38, 500-516.

Sinclair, R.R., Sparling, C.E., Harwood, J., 2020. Review of Demographic Parameters and Sensitivity Analysis to inform Inputs and Outputs of Population Consequences of Disturbance Assessments for Marine Mammals, In: Rep, S.M.a.F.S. (Ed.).

Stöber, U., Thomsen, F., 2019. Effect of impact pile driving noise on marine mammals: A comparison of different noise exposure criteria. The Journal of the Acoustical Society of America 145, 3252-3259.
Thomas, L., Russell, D.J.F., Duck, C.D., Morris, C.D., Lonergan, M., Empacher, F., Thompson, D., Harwood, J., 2019. Modelling the population size and dynamics of the British grey seal. Aquatic Conservation: Marine and Freshwater Ecosystems 29, 6-23.
Verfuss, U.K., Sparling, C.E., Arnot, C., Judd, A., Coyle, M., 2016. Review of Offshore Wind Farm Impact Monitoring and Mitigation with Regard to Marine Mammals, Springer New York, New York, NY, pp. 1175-1182.

Justification

Report C055/22
Project Number: 4315100126

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: 6 October 2022

Approved: Drs. Jakob Asjes
MT Member Integration

Signature:

Date: 6 October 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

With knowledge, independent scientific research and advice, **Wageningen Marine Research** substantially contributes to more sustainable and more careful management, use and protection of natural riches in marine, coastal and freshwater areas.

Wageningen Marine Research is part of Wageningen University & Research. Wageningen University & Research is the collaboration between Wageningen University and the Wageningen Research Foundation and its mission is: 'To explore the potential for improving the quality of life'