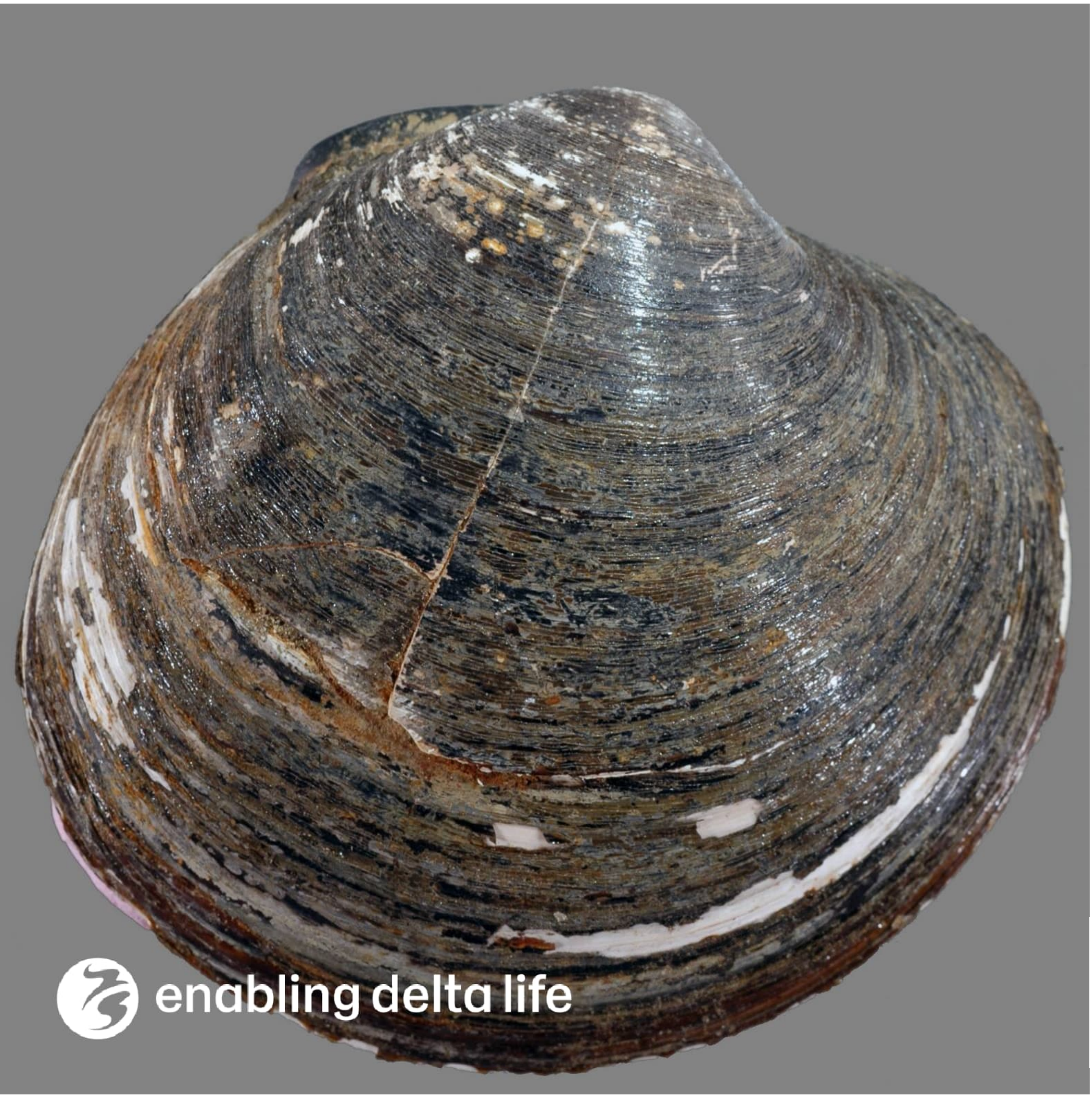
Mapping *Arctica islandica*



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Summary

The ocean quahog *Arctica islandica* is a long living, slow growing species. There were several indications that this species is negatively affected by intensive bottom trawling activities in the North Sea, but previous efforts of linking species distribution to fisheries efforts did not yield clear-cut results. Since March 2023 several areas in the Dutch part of the North Sea have been closed for bottom trawling, as a measure to protect North Sea nature. This study aims to assess the potential habitat suitability of the ocean quahog, its susceptibility to fishing and hence the potential benefit of the currently closed areas for fishing.

Available data on the presence and absence of *A. islandica* in the Dutch EEZ and the rest of the southern North Sea were compiled and used database to estimate the habitat suitability for the species. Logistic regression and random forest regression methods were used to link ocean quahog distributions to environmental characteristics such as bottom shear stress from currents, depth and bathymetric structures, sediment grain size composition and temperature. To assess the temporal changes in the spatial distribution of *A. islandica* in relation to changes in fisheries effort, the data sets were split into two: before and after 2003. Separate habitat suitability models have been fitted for both periods, and the two models have been compared spatially. The map of time differences has been compared to the spatial distribution of fisheries effort.

Comparison of older (up to 2003) and newer (after 2003) data shows that the distribution area of the species has decreased. Despite the higher catch efficiency of the newer sampling gear, virtually no animals have been caught in the Frisian Front area, where previously the species was regularly found. The strongest decline in spatial distribution of the species corresponds with the most heavily fished areas of the Southern North Sea.

The newly established Marine Protected Area in the Frisian Front is part of the area where the species has disappeared over the years. It is expected that the species will be able to recover in this area, although this will take time due to its slow growth rate. Monitoring of this area will be essential to confirm this.

Inhoud

1 Introduction

Demersal fisheries using beam trawls with tickler chains is intensively practiced on the Dutch Exclusive Economic Zone (EEZ) in the North Sea. These fisheries disturb the top layers of the sediment and endanger the benthic animals living in these layers. Previous studies of these effects have shown that not all species are equally vulnerable. In particular, large and long-lived species are most likely to be negatively affected by the fisheries (Rijnsdorp et al., 2018). Effects further depend on the position of the animals in the sediment, their fragility and their size (Bergman and van Santbrink, 2000).

The ocean quahog, *Arctica islandica*, is an emblematic species often mentioned as a typical example of a benthic species most vulnerable to disturbance by fisheries. *A. islandica* is a species with extreme longevity. Ages up to 504 years have been recorded (Butler et al, 2013). For the Dutch part of the North Sea ages of slightly over 150 years can be found. Ages of 40 to 80 years are common (Witbaard, 1997). At an age of 7 to 10 years they become sexually mature (Rowell et al, 1990) and reproductive success in many areas of the North Sea is irregular although settlers are regularly found. Their survival is apparently low (Witbaard & Bergman, 2003). Specimens of a few cm in size are hardly found and never in high densities like in the Baltic Sea, northern Norway or northern North Sea. The species habitat in the Dutch EEZ is confined to deep, low-dynamic and summer-stratified areas. The 30-meter depth contour south of the Frisian Front forms the southern distribution limit in the North Sea. This coincides approximately with the 16 degrees summer isotherm, which is mentioned as distributional limit along the US and Canadian east coast (Mann, 1982). For the distribution in the southern North Sea this might imply that ongoing climate change might lead to a gradual northward shift of this southern distribution limit.

1.1 Ecological characteristics

A. islandica feeds on sedimenting organic matter. Because of its large body size with reserves, long periods without food can be overcome. The species has short siphons and lives most of the time buried within the surficial sediment. Because of this position in the sediment and the large size of the adults it is sensitive to bottom trawling (see also Rijnsdorp et al., 2018).

Arctica islandica has been recognized as a locally endangered species and has been listed by OSPAR in recommendation 2013/5. This recommendation aims at better protecting and restoring the population in the wider North Sea and Celtic Seas (Region II and Region III1). As a consequence of this nomination, contracting parties within OSPAR should undertake action to "strengthen the protection of the ocean quahog at all life stages in order to recover its population, to improve its status and to ensure that the population is effectively conserved". Suggested actions involve the possibility to introduce legislation to protect the ocean quahog in all its life stages; collaborating on recommended monitoring strategies; facilitating and improving research and collecting trend data on populations and distribution of ocean quahog using suitable sampling methods to obtain quantitative reliable density estimates such as the combination of 'triple-D' dredges and box cores; working towards mapping and assessment of population size of existing ocean quahog distribution; compiling overviews of historical data of the distribution and density of ocean quahog, and strive towards the preparation of maps/models indicating the possible former distribution of this species, the delineation of potential Marine Protected Areas (MPA) for the conservation and recovery of the ocean quahog, and inclusion of such as a component of the OSPAR MPA network; introduction of the ocean quahog as a protected species under regional and international biodiversity conventions.

Within the Dutch EEZ, a monitoring is in place and several marine protected areas have been assigned. One of these areas (Oyster Grounds) has been assigned in a local hotspot of its present-day distribution.

It will be evident that for protection and management of this species reliable distributional maps should be available. A first compilation of distributional data was made by (Witbaard,1997, PhD thesis). In 2003 Witbaard and Bergman updated this information with more recent data and combined trawl, dredge and boxcore data. Between 2006 and 2012 NIOZ started a project to map large (>6 mm) benthic species on the Dutch EEZ exclusively using the Triple D dredge (Witbaard et al, 2013) and since 2018 BIOMON (RWS) selected areas of the Dutch EEZ i.e. (nominated) MPA's, were sampled with this gear. Thus, since 2003 a wealth of new data has become available on the present day and historical distribution of *Arctica islandica*. Historical, previously unused data, extracted from NIOZ cruises and personal notifications to the authors have been added to the data compilation. This resulted in a dataset composed of presence-absence data based on Boxcore samples, Trawl samples and Triple D dredge samples that covers the period between 1972 to 2022. The older data are usually collected with less efficient methods. The newer data (since 2003) have mainly been collected with the Triple D dredge, which is a highly efficient gear to catch *Arctica*.

1.2 Objectives

The aim of the present study was to compile all available data on the presence and absence of *Arctica islandica* in the Dutch EEZ and the rest of the southern North Sea, and to use this database to estimate the habitat suitability for the species. The approach followed the workflow of Herman and van Rees (2022). EMODnet Biology compiled data sets on presence/absence of the species in the southern North Sea, complemented with local datasets not yet included into EMODnet, were used to fit spatial distribution and habitat suitability models. Logistic regression and random forest regression methods were used. Environmental data representing bottom shear stress from currents, depth and bathymetric structures, sediment grain size composition and temperature were used as independent variables in these regression approaches.

Fishing intensity was mostly low in the start of the sampling period. It peaked in the late 1980ies and 1990ies. After that period, a gradual change occurred in fishing intensity because of the introduction of pulse fishing. In comparison to traditional beam trawling with tickler chains, this type of gear has a more limited bottom impact. Less surface area is swept because the gear is highly efficient in catching flatfish. In 2019, with a transition period to 2021, pulse fishing was banned. Some beam trawlers returned to gears with tickler chains, but because of the high fuel consumption and decreased area of fishing grounds (due to Brexit, windfarms and MPAs) many beam trawlers have stopped their activity. At present no detailed information is available yet on the fishing intensity after these changes.

In order to illustrate temporal changes in the spatial distribution of *Arctica islandica*, while preserving sufficient data coverage to obtain reasonably detailed maps, the dataset was split in two parts: before and after 2003. Separate habitat suitability models have been fitted for both periods, and the two models have been compared spatially. The map of time differences has been compared to the spatial distribution of fisheries effort.

2 Material and Methods

2.1 EMODnet data

Available occurrence data for the species have recently been compiled in the framework of EMODnet Biology (Herman et al., 2020). By carefully selecting the data sets that have, in principle, assessed the entire macrobenthic community (or for a well-defined part thereof, e.g. all shellfish), the presence-only database has been transformed into a presence/absence dataset. It has been assumed that wherever a sample targeting the entire macrobenthic community has been taken, all macrobenthic species not recorded in the sample were actually absent in the sample. Therefore, all these species have been attributed an 'absence' record in all community samples where they have not been found. In total, more than 60 data sets covering almost 100,000 samples have been collected in the Greater North Sea, which also includes the Irish sea and part of the N.E. Atlantic. The number of samples in the North Sea proper is around 20,000.

2.2 Older NIOZ data

The newer NIOZ data are all based on sampling with the triple D dredge (Bergman & van Santbrink, 1994). The gear is well suited to make density estimates of sparsely distributed species because it samples bottom surfaces of 10 m² to 20 m² up to 20 cm depth over a track length of 50 to 100 m. In terms of area sampled, a typical 100 meter haul with this gear equals 260 boxcores. The long sampling trajectory minimizes the effects of spatial heterogeneity on that scale. The gear only samples larger animals (>6mm) which are generally longer-lived animals better able to reflect long term trends in their environment. Especially bivalves, like *Arctica islandica,* have a high catch efficiency. For some research projects, track lengths were reduced to 80 or 50 meter (16-10 m²). This means that the chance to find a rare species is influenced. However, over the last 20 years the number of stations on the Dutch EEZ which are sampled with the triple D is large enough to compensate for this effect to obtain a reliable data set on presence and absence of a species.

Table 2.1: Origin of distributional data for Arctica islandica observed and / or collected during other research programs and which are not included in the Triple-D database.

Ship	IDcruise	Year/MM/DD	Scientist	Ref	Project
Aurelia	-	1972-1980	F.Creutzberg	Noort et al, 1979-1986	NIOZ
Aurelia	-	1981/05/11	P.Wapenaar		NIOZ
Tyro	-	1983/05/01	P.de Wilde		REFLEX
Pelagia	-	1983/08/16	T.v.Weering		ENAM
Tyro, Heincke e.a	-	1986	Various	Künitzer, 1990	ICES Synoptic mapping
Aurelia/Holland	-	1986/04	R.Heijman		NIOZ-PhD
Aurelia/Holland	-	1986/08	R.Heijman		NIOZ-PhD
Aurelia/Holland	-	1986/09	R.Heijman		NIOZ-PhD
Aurelia/Holland	-	1987/04	R.Heijman		NIOZ-PhD
-	-	1989/05/02	G.v.Moorsel	vanMoorsel 1991.	BuWa-RWS
-	-	1989/09/27	G.v.Moorsel	vanMoorsel, 1993.	BuWa-RWS
RWS schip?	-	1990	R.Daan		Boorspoeling
Tridens	-	1990/08	M.Fonds		Impact
Pelagia	-	1990/10	G.Duineveld		
Endevour?/Darwin	-	1991/08	A.Rowden		UK Vaartocht
Pelagia	-	1991/11/21	B.Kuipers		Shetlands
Pelagia	-	1992	L.Bolle		DB92/
Pelagia	-	1992/01/06	L.Bolle		DB92/1
Pelagia	-	1992/02/10	V.Raaphorst		BELS
Pelagia	-	1992/03/26	L.Bolle		DB92/3
Pelagia	-	1992/05	L.Bolle		DB92/5
Pelagia	-	1993	H.v.Haren		Cursus
Pelagia	-	1993/11/16	R.Witbaard		Silverpit
Pelagia	-	1993-1996	A.Boon		VVA
Pelagia	-	1994/06/14	P.de Wilde		Cursus
Pelagia/Mitra	64PE111?	1997	M.Bergman		BEON
TX 66	-	1998/10	R.Klein		TX 66
Pelagia	64PE128	1998/12	M.Bergman		FrieseFront
Pelagia	64PE133	1999/03	K.Booy		PASOC/Schar
Pelagia	64PE137	1999/05/03	R.Daan		PROCS99-I
Pelagia	64PE139	1999/04	G.Duineveld		PASOC/Schar,
Pelagia	-	1999/06/09	R.Witbaard		NIOZ
Pelagia	64PE142	1999/07	M.Baars		Plume&Bloom
Mitra RWS	-	1999/09	M.Baars		Plume&Bloom
Pelagia	64PE163	2000/05	R.Witbaard		NIOZ
Pelagia	64PE181	2001/06	M.Baars		Plume&Bloom
Pelagia	64PE438	2018	Witbaard		NICO10
-	-	1989-1997	Witbaard	Witbaard, 1997	PhD Thesis
-	-	1989-2003	Witbaard & Bergman	Witbaard & Bergman, 2003	-

2.3 Environmental data

Environmental information is needed as a basis for species distribution models. For this project, we rely heavily on a recent compilation of North Sea wide environmental information by Van der Reijden et al. (2018). These authors have compiled their datasets on bathymetry, grain size distribution, temperature and salinity from diverse literature sources. They have made their data available in the form of geo-tiff files, that we have downloaded for use in the present project. In the files, there is also information on bottom shear stress, but this is based on a rather coarse model. We have replaced it with results of the Deltares DCSM-FM model for the greater North Sea. The datasets used are listed in Table II. Sources of the data are Van der Reijden et al. (2018) for calculations of 'Bathymetric Position Index' values based on bathymetry, Stephens (2015) for grain size data, Copernicus marine services (www.marine.copernicus.eu) for salinity and temperature, EMODnet bathymetry (http://portal.emodnet-bathymetry.eu/) for basic bathymetry, Deltares for bottom shear stress calculated with DCSM-FM. The version of DCSM-FM used is the same as that deployed for Herman and van Rees (2022) and was run in 2020.

The 'BPI' (Bathymetric position index) calculates for each point, the difference of the depth of the point with the average depth of the surrounding area, where the surrounding area is a circle with a fixed radius. BPI5 uses 5 km as a radius for the surroundings, and similar for the other BPI variables. Van der Reijden et al. (2018) also define a weighted average BPI, but we did not use that in our analysis.

Temperature difference is a measure for the change in temperature between 2008 and 2013. This is not distributed homogeneously over the North Sea. Atlantic water has warmed very little, whereas the North Sea has been warming considerably over the past decades. Consequently, the largest temperature differences are seen in the eastern and north-eastern parts of the North Sea.

No temporal (e.g. seasonal) variance of salinity and temperature has been used in the present study. It is known that variation of these variables is often very important in estuarine conditions. However, in the North Sea the ranges are much more limited.

Table 2.2: Environmental data and their source

Env.Variable	Explanation	Source
Depth	Depth at 178 m resolution	EMODnet
BPI5	Bathymetric Position Index 5 km	vdReijden2018
BPI10	Bathymetric Position Index 10 km	vdReijden2018
BPI75	Bathymetric Position Index 75 km	vdReijden2018
Bott.shr.stress	Bottom shear stress from currents	DCSM-FM
Salinity	Mean Salinity	Copernicus
Temperature	Mean Temperature	Copernicus
Temp.diff	Temperature Difference over the year	Copernicus
Gravel	Fraction gravel in sediment	Stephens2015
Mud	Fraction Mud in sediment	Stephens2015
Sand	Fraction Sand in sediment	Stephens2015

2.4 Information on fisheries effort

Although fisheries intensity data were provided by van der Reijden et al. (2018), we used a more recent compilation prepared by ICES and published by EMODnet Human Use. It shows fisheries intensity estimated from VMS data in 2022. The intensity is estimated as average area swept with the subsurface part of bottom-disturbing gear types. More details on the dataset can be found in https://ows.emodnet-humanactivities.eu/geonetwork/srv/api/records/d57fbdea-489e-4e11-9ff1-f0f706cfe783.

2.4.1 Time periods used for statistical analysis

Analyses of the occurrence data of A. islandica were split in two time periods: prior to 2003 (corresponding to the 'old NIOZ data') and post-2003 (corresponding to the 'newer NIOZ data'). Time splitting was required to investigate possible fishing effects (see below), but the periods used are required to present sufficient spatial cover of the Dutch

EEZ. Finer splitting would have resulted in biased data sets, where large spatial gaps in the data could have resulted in wrong interpretations of the probability of occurrence. By splitting around the year 2003, the methodological change towards the use of the Triple-D dredge coincides with the change in time periods. This aspect is taken care of in the discussion.

3 Statistical analysis

In this analysis, we applied two regression techniques: logistic regression and random forest regression. Results of both approaches are given. They are compared for unexpected deviations, that could point to flaws in the fitting.

A multivariate logistic model was fitted using the generalized linear modeling function “glm” in R, and assuming binomial distribution of the presence/absence dependent variable. All available environmental data were used in the analyses, with the exception of gravel and sand content, which did not contribute to the explanation (increase of AIC after inclusion in the model) and are colinear with mud content. The squares of all environmental variables have been added to the model, allowing for Gaussian-type responses of the species to the environmental variable.

Random Forest models were fitted using the R package randomForest. Although the dependent variable (presence/absence) is a binary variable, the Random Forest was run in regression mode, as the aim was to obtain the probability of occurrence calculated by the model. The number of variables used at each try in the random forest is a parameter that can influence the performance of the method. After extensive checking, the default number of variables (3) appeared to be the optimum and was not changed. The number of random trees generated in the forest was 1000.

For both periods, a raster with the model predictions was plotted and visually compared with the observations. The change over time was visualized by plotting the difference between the two rasters, one per time period. This difference value was visually compared with the spatial pattern in fisheries effort.

3.1 Data and code repository

After completion of the project, all data and scripts used in the analysis will be made available from the 4TU repository.

3.1.1 Visualizing species-environment relations

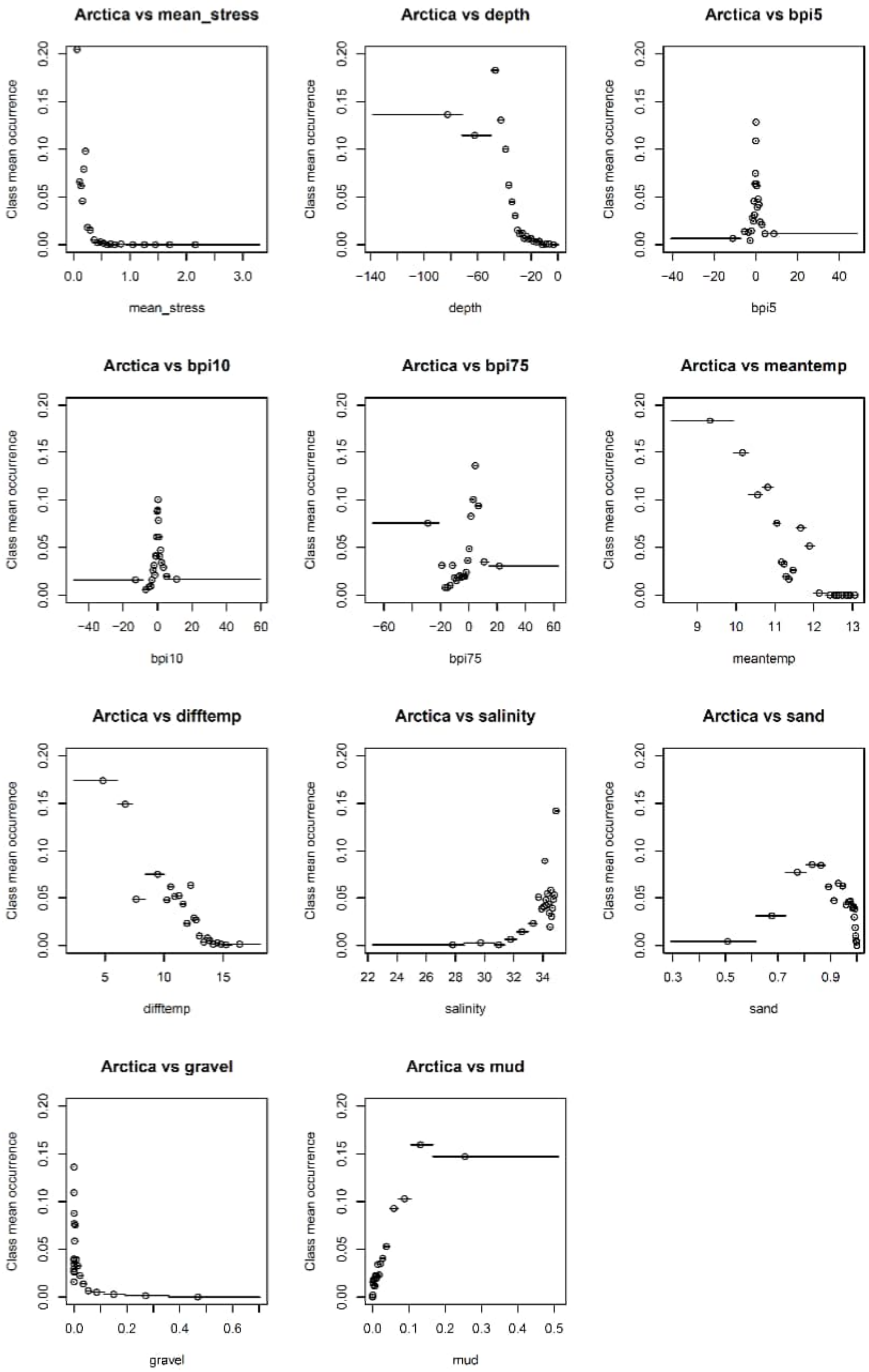

Figure 3.1: Raw plots of occurrence fraction versus environmental variables. Shown are the fraction presences per 5-percentile class of the environmental variable, across all years and spatial positions.

As a preliminary analysis, plots are produced showing the raw data of species occurrence versus the environmental factors in the database (Figure 3.1). In these plots, no distinction is made between the time periods. It can be seen on the plots that *A. islandica* (in the North Sea) prefers sites with low bottom shear stress, a depth of more than 30 m, not protruding in height above the surroundings at scales of 5-10 km, but slightly protruding at larger scales, with low temperature and restricted temperature change, high salinity and sandy sediments with a relatively high (> 20%) mud content.

3.2 Regression analysis of presence data

In the course of time, the occurrence of *A. islandica* in the Dutch EEZ has become rarer and spatially more restricted (Figure 3.2). The species is currently only routinely found in the Oyster grounds, the deepest part of the EEZ. It has almost disappeared from the Frisian Front area, the southernmost part of its distribution where it used to be quite well-spread and abundant. It was, and still is, occasionally observed in the areas just south of the Dogger bank. With very few exceptions, there are no observations from the area shallower than 30 m in the coastal zone.

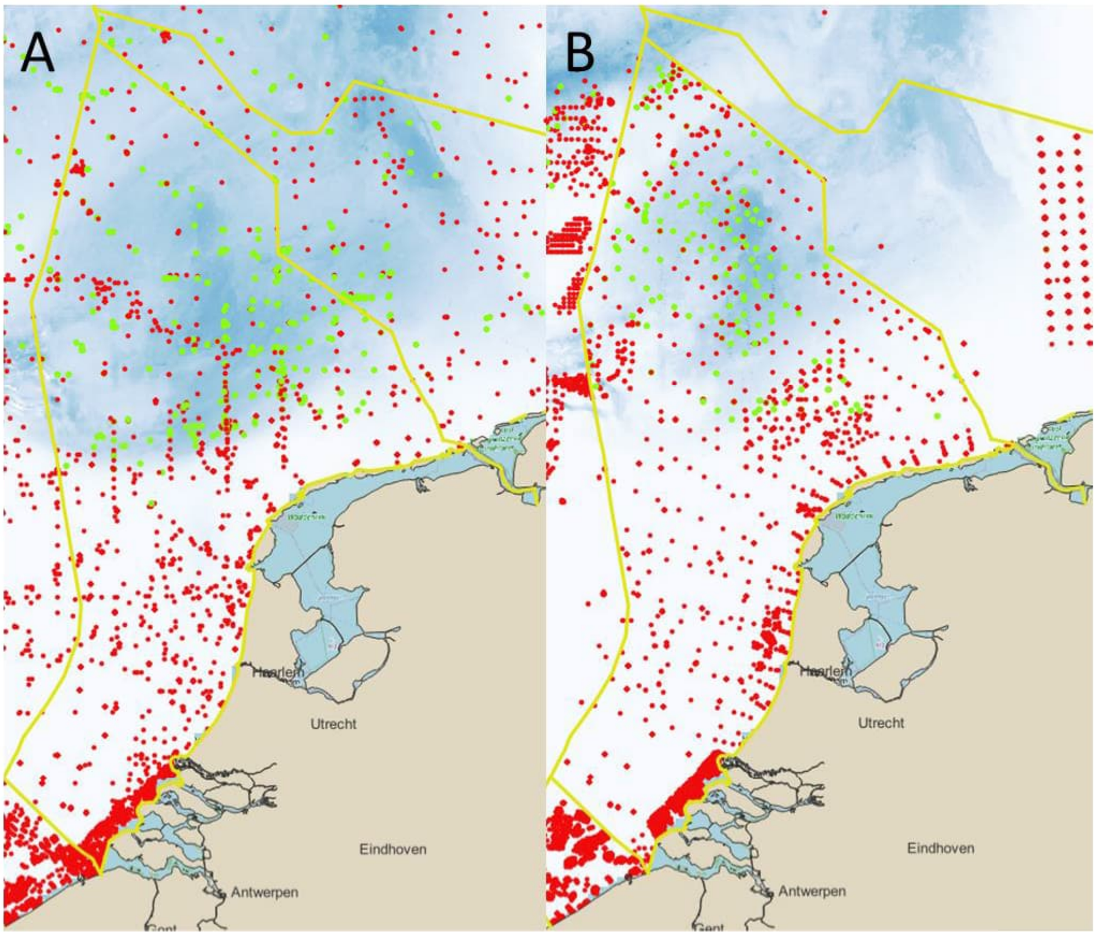

Figure 3.2 Observed occurrence of A. islandica in A. period up to and including 2003 and B. period after 2003. Green dots indicate samples with the species present, red dots are absences. Blue shading represents predicted probability of occurrence using a logistic regression model. Darker blue represents a higher chance of finding Arctica islandica.

Most environmental variables were significant in at least one of the two logistic regression models (Table 3.1). They were kept in both models for consistency. Salinity was not formally significant in either of the two cases, but removing it from the model resulted in a higher AIC in both cases.

Table 3.1 Summary of logistic regression model of data pre-2004

		Pre-2003		Post-2003	
	terms	coef	Pr	coef	Pr
(Intercept)	(Intercept)	-48.4752		-421.8581	*
mean_stress	mean_stress	0.4296		-14.1400	***
I(mean_stress^2)	I(mean_stress^2)	-25.4441	**	3.5093	
depth	depth	-0.1000	***	-0.1648	***
I(depth^2)	I(depth^2)	-0.0009	***	-0.0014	***
I(bpi5^2)	I(bpi5^2)	-0.0223	*	-0.0102	***
bpi10	bpi10	-0.0574	*	0.0480	***
I(bpi10^2)	I(bpi10^2)	0.0104	*	0.0087	***
bpi75	bpi75	-0.0107		-0.0400	***
I(bpi75^2)	I(bpi75^2)	0.0000		-0.0005	.
meantemp	meantemp	0.4703		22.5488	***
I(meantemp^2)	I(meantemp^2)	-0.0275		-1.0415	***
difftemp	difftemp	-0.2421		-1.9584	***
I(difftemp^2)	I(difftemp^2)	0.0171		0.0846	***
salinity	salinity	2.1310		17.4680	
I(salinity^2)	I(salinity^2)	-0.0251		-0.2498	
mud	mud	8.5407	***	17.6845	***
I(mud^2)	I(mud^2)	-16.5783	**	-49.2662	***

The predictions from the random forest regression (Figure 3.3) are more pronounced with extremer high and low values, compared to the logistic regression fitting. Random forest models are not constrained to adopt a smooth form with respect to the environmental variables and can thus better represent non-linearities in these relations. The spatial patterns shown, however, are similar between the two methods.

The disappearance of *A. islandica* from the central part of the Frisian Front is much clearer in the random forest model. Also in the northern part, between Oyster Grounds and Dogger Bank, a reduction of the probability of occurrence is predicted.

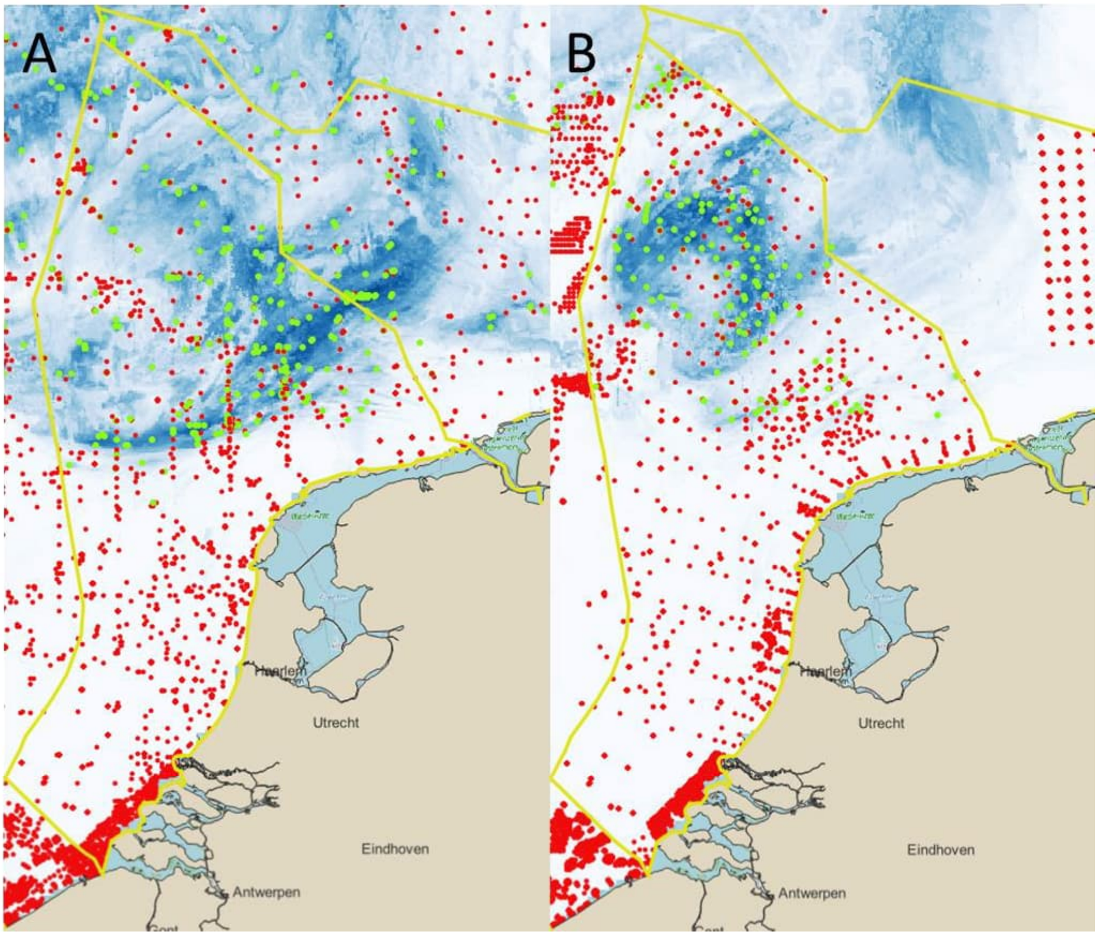

Figure 3.3. Observed occurrence of A. islandica in (A) period up to and including 2003 and (B) period after 2003. Green dots indicate samples with the species present, red dots are absences. Blue shading represents predicted probability of occurrence using a random forest regression model. Darker blue represents a higher change of finding A. islandica.

Mean bottom shear stress, depth, mud content of the sediment and mean temperature are the most important environmental variables in both models. However, the other variables do not greatly differ in importance, according to the two measures provided. None of the variables was discarded as irrelevant during the fitting process.

3.3 Difference between time periods

The random forest models for the two periods were used to calculate the change in predicted probability of occurrence between the two periods. In the difference plot (Figure 3.4 two observations can be made. The probability of finding the species in a sample has increased in the central Oyster Grounds, the area where the species is most consistently found. The higher probability calculated probably reflects the more reliable gear used in the more recent period: the NIOZ triple D dredge is highly efficient in finding the species when it is present, and this efficiency exceeds that of the gears used before.

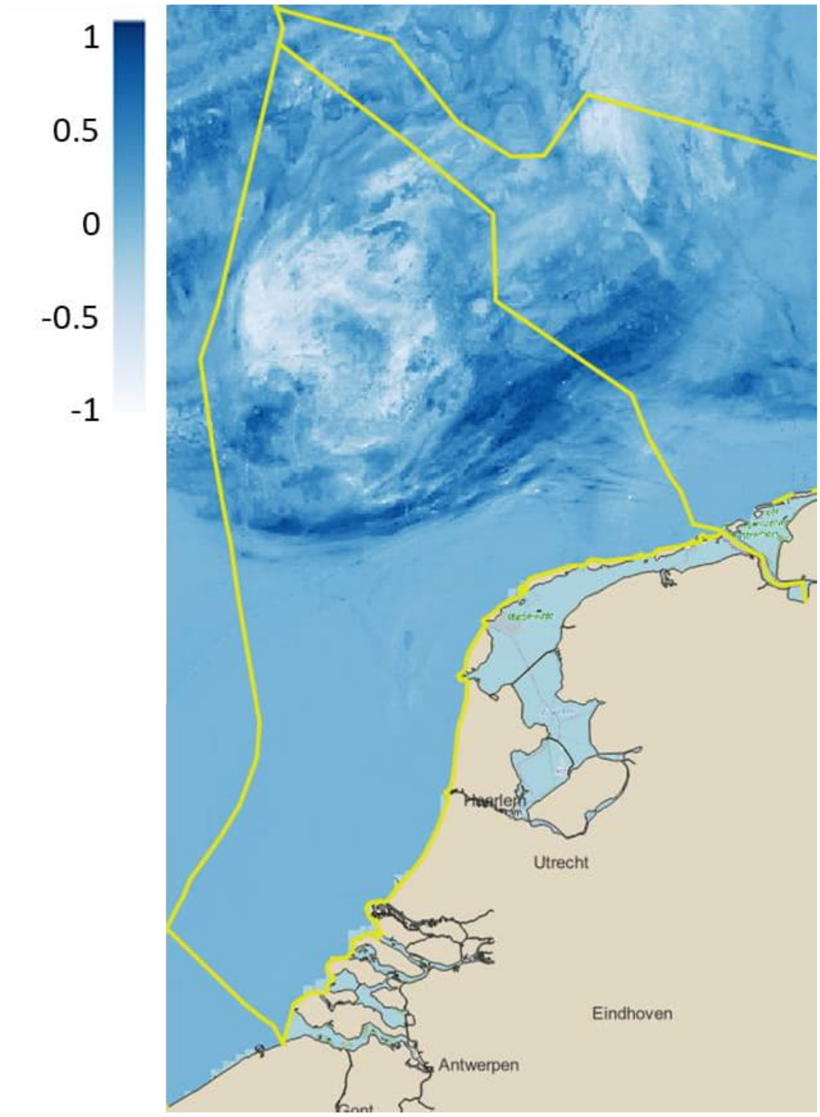

Figure 3.4. Difference in predicted occurrence probability of A. islandica in the Dutch EEZ. The values shown are based on the random forest predictions and show the probability prior to 2003 minus the probability after 2003. Positive (dark) values indicate disappearance, negative (light) values increased probability to find the species.

The second observation is that around the Oyster Grounds, and especially in the Frisian Front, the probability of finding the species has declined. This is despite of the apparently higher catch efficiency of the Triple D. The decline is therefore a conservative estimate. Such decline was previously described by Witbaard & Bergman (2003) and substantiated by Leslie model estimates (Witbaard, 2007) using survival and mortality estimates derived from literature and experimental trawling (Lindeboom & Groot, 1998, Fonds, 1991). On basis of that Leslie model, it was predicted that *A. islandica* population in the Frisian front would be virtually extinct in 2017 (Witbaard, 2007).

3.4 Relation with fisheries

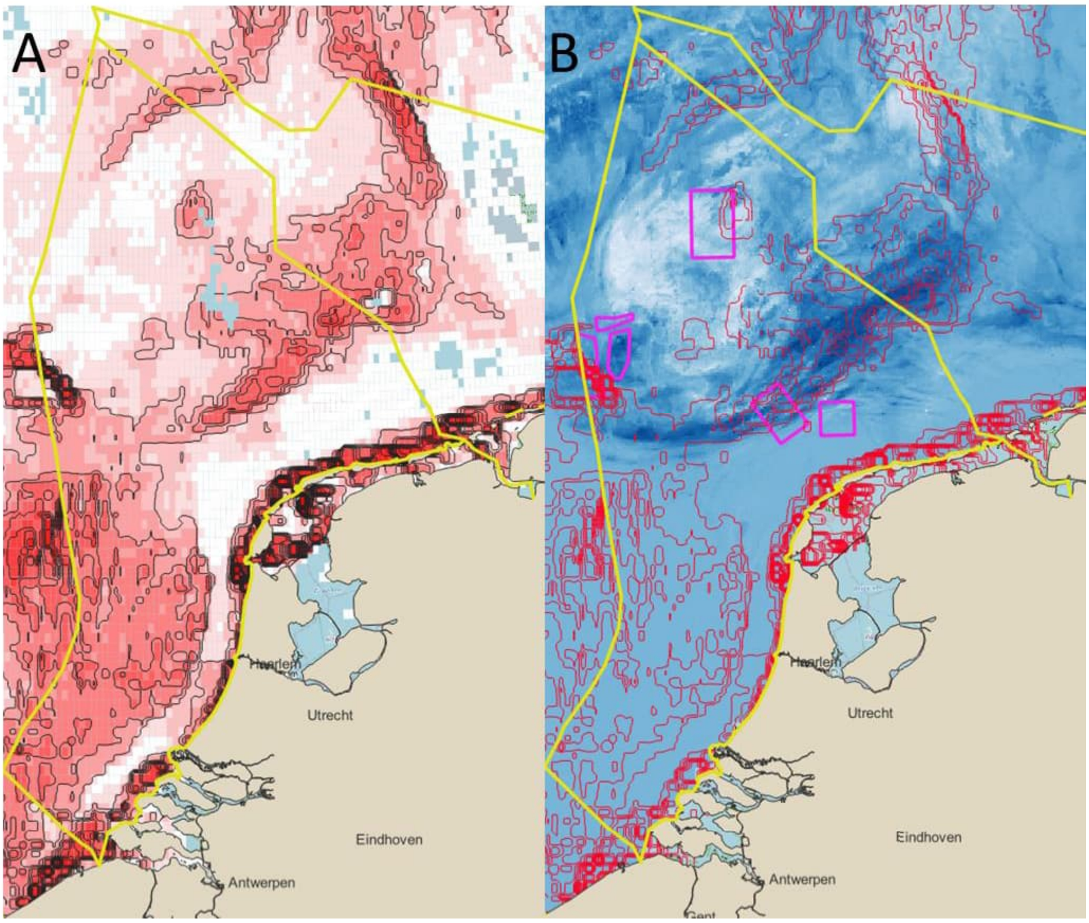

Figure 3.5. (A) Spatial pattern of fisheries effort, in terms of average area swept by the below-surface part of the gear. Based on ICES calculations and provided by EMODnet. The graph shows the intensity, overlaid by contour lines that summarize the graph. (B) change in probability of occurrence of A. islandica between the two time periods studied, overlaid by the contours of fishing intensity. Also indicated in purple are the recently installed fisheries-free zones in the Dutch EEZ.

An important question is whether the change in occurrence patterns of the species is related to fisheries effort and negative effects of fisheries gear on the mollusk. It was not possible to reconstruct fisheries effort for the entire period for which we have biological observations. We therefore concentrated on recent spatial patterns in fishing efforts and compared it with patterns of change in *A. islandica* (*Figure 3.5*).

4 Discussion

We used the logistic regression results mainly as a control of the random forest models. Random forest regression models are more versatile and better able to catch non-linearities in the responses. However, they are vulnerable to overfitting and may provide spurious results in data-poor areas. For this reason, we also present both models in the present report. However, we consider the random forest predictions as the main results of this project.

4.1 Effect of fisheries?

Differences in predicted spatial distribution can be caused by an external factor, such as fisheries, but can also be caused by differences in the underlying datasets.

While the presented distributional data for *A. islandica* cover decades long period, the fishery intensity maps used in this study only cover 2018-2022. The spatial similarity of fishing intensity maps for the time period 1999-2002 (Figure 6) and 2018-2022 (Figure 5) shows that the distribution on a larger scale remained rather similar, despite the various transitions which have taken place within the fishing fleet. The similarity in the spatial distribution of fishing is to a large extent due to the strong relationship between (local) primary productivity and fishing (van Kooten et al, 2015) and it is therefore reasonable to assume that recent maps on fishery intensity also reflect distributional patterns further back in time.

The spatial coverage of benthos sampling in the North Sea as a whole, was not the same in the two periods. However, within the Dutch EEZ, spatial coverage was sufficiently even to assume a reasonable estimate from the models. We therefore concentrated our analysis on this zone only. Furthermore, the sampling methods differed between the two time periods. Although presence/absence information is less sensitive to methodological differences than numerical abundance, it is still determined by the capture efficiency of the devices. The most recent data were collected with the deep digging dredge (Bergman & Santbrink, 1994) that can be assumed to be more efficient than the grabs and surficial dredges and trawls deployed earlier. We would therefore expect to find a general increase in probability of presence in the recent dataset, at least for those regions where the species occurs. Nevertheless, absence was often recorded in parts of the Frisian front where the species was routinely found before. Probability of presence in the Oyster Grounds, however, was more elevated in the recent data, probably as a consequence of higher sampling intensity on top of the higher capture efficiency and/or a more even distribution of sampling points. This interpretation suggests that our results are a conservative estimate. However, proper statistical testing of the conclusion is difficult, as the change in methodology coincides in time with the transition between the time periods used in this analysis.

Although the above comparison is correlative, the coherence in the spatial patterns is very striking and corroborates the earlier observation made by the superposition of *Arctica islandica* densities on maps reflecting the fishing intensity between 1999 and 2002 (Figure 4.1, from Witbaard et al., 2007).

Apart from the striking overlap in spatial patterns between the presence/absence of *Arctica islandica* and fishing intensity, ample evidence shows that *A. islandica* is extremely sensitive to bottom penetrating fishing gears such as beam trawls with tickler chains, but also otter trawls (Rumohr & Krost, 1991). The shallowly buried mode of living makes the shells extremely vulnerable to passing tickler chains. The shell size of adult *Arctica* is also such that they are well retained in the nets of commercial beam trawl gears. Analyses of injuries on dead and freshly dead shells collected on the Frisian Front and Oyster Grounds showed that between 80 and 90% of injuries is found on the posterior shell side. This is the shell side where the siphons are located. It looks upward at the sediment-water interface (Klein & Witbaard, 1993; Witbaard en Klein, 1994). This side is the most vulnerable to be hit by tickler chains.

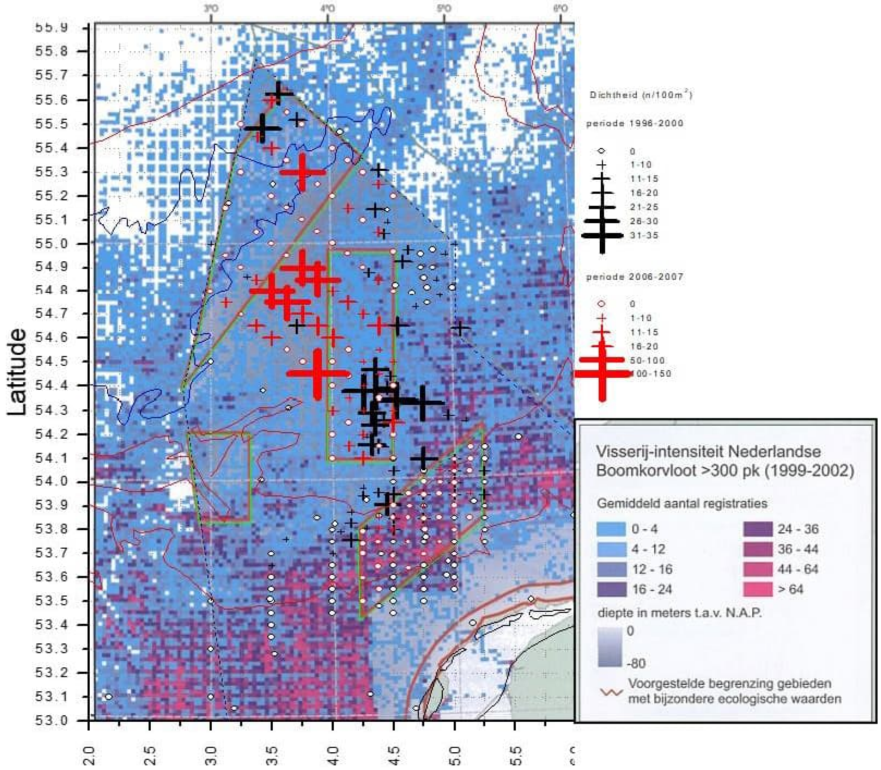

Figure 4.1: Overlayed maps of observed densities of Arctica islandica (Witbaard & Bergman, 2003) and fishing intensity of the Dutch beam trawl fleet between 1999 and 2002 (Lindeboom et al, 2005).

Figure 4.2: . Impression of the Arctica catch collected with a commercial rigged gear on board of RV Tridens.

Observations on board of research and fishing vessels corroborate that up to 80 % of the animals in the catch become damaged during fishing or while the catch is being sorted on board (Figure 4.2). It is poorly known what percentage of damaged animals remains on the seafloor and is not retrieved from the seabed. Repeated trawling over the same area suggests that in the first trawl passage 10% of specimens present in the track are brought on deck (Lindeboom & de Groot, 1998).

Scars on the inside and outside of shells were a common feature in shells which were collected on the Frisian Front and in the southern Oyster Grounds. Witbaard and Klein (1994) and Klein and Witbaard (1995) were able to reconstruct a timeseries on basis of the occurrence of scars by using the annual internal growth lines. The correlation of this time trend with the development of the Dutch beam trawl fleet was highly significant (R=0.76, p<0.01). Bottom disturbance not only damages and injures adult shells, but small juvenile shells are likely to be crushed completely and the continuously disturbed bottom sediments furthermore limit the growth of spat, which might explain the absence of juvenile shells of a few cm (Witbaard & Bergman, 2003).

It is not only *Arctica islandica* which evidences the effects of heavy bottom trawling gears. Figure 8 shows a compilation of heavily damaged and repaired shell species encountered in samples from the southern North Sea. Scars are also found in large gastropods such as *Neptunea antiqua* and *Buccinum undatum* (see also Mensink et al., 2000). Injuries and damage is also observed in non-mollusk taxa, indicative for the ecosystem wide effect of bottom trawling.

Figure 4.3: Examples of damaged and repaired shells. Left to right; Arctica islandica, Acanthocardia echinatum and Chlamys opercularis.

4.2 Future

For maintenance or restoration of the *Arctica islandica* population it is essential to have local successful reproduction or regular import of larvae from neighbouring areas. For a broadcast spawner like *Arctica islandica*, successful reproduction is only possible when densities of adults are sufficiently high to ensure fertilization as sperm and eggs meet passively during the spawning event. There is however no knowledge about the minimum adult densities needed for such successful fertilisation. Populations where both juveniles (<50mm) and adults (>50mm) are abundantly present have densities which range between 30 and 300 individuals per m². These densities are much higher than what is found in the Dutch EEZ. Self-sustainability of the “Dutch” *Arctica* population thus seems questionable, but it cannot be excluded that local small pockets with high densities form a local source in for instance the central and northern part of the Oyster Grounds. In the absence of local larval production, it is possible that a population (sink) is sustained by the import of larvae from elsewhere. This might also be the case for the Oyster Grounds. Measured larval development for *Arctica* lasts between 32 and 62 days (Lutz et al, 1982; Landers, 1976), thus dispersal over considerable distances is possible which could mean that the Oyster Ground population, is being fed with larvae just north of the Doggerbank. In both situations the survival of spat should also be high. Survival can be promoted by limiting bottom disturbance by for instance closing areas for bottom trawling. *Arctica islandica* is a long-lived species with known irregular successful spatfalls. This means that recovery might take a long time but limiting bottom disturbance in specified areas (MPA’s) is deemed to be a valid instrument to safeguard the population for the future.

5 Conclusions

We have constructed species distribution models for *A. islandica* based on a compilation of different data sources. Apart from international data summarized in the EMODnet data base, we have used data from old NIOZ cruises, as well as an extensive database collected from deployment of the Triple-D dredge.

Comparison of older (up to 2003) and newer (after 2003) data shows that the distribution area of the species has decreased. Despite the higher catch efficiency of the newer sampling gear, virtually no animals have been caught in the Frisian Front area, where previously the species was regularly found. The strongest decline in spatial distribution of the species corresponds with the most heavily fished areas of the Southern North Sea. This disappearance of the species from the Frisian Front area is in line with earlier predictions and with observations of the devastating effect of fisheries disturbance on this species.

A newly established Marine Protected Area in the Frisian Front is part of the area where the species has disappeared over the years. It is an interesting subject of future monitoring to investigate whether the MPA establishment can contribute to the restoration of this species in part of its former distribution area.

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