Management options for brown shrimp (*Crangon crangon*) fisheries in the North Sea

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Summary

Fisheries targeting brown shrimp (*Crangon crangon*) in the North Sea in European waters are largely unregulated in terms of landings and effort. A license system exists, but this did not prevent the current situation of overcapacity of the shrimp fleet. The governments of the North Sea brown shrimp fisheries (Netherlands, Germany, Denmark, Belgium, United Kingdom) have shown little interest in management of the shrimp fisheries, which leads to a consequent lack of action to establish a management system for shrimp, as well as little resources for research and monitoring. Initiatives in the Netherlands of the industry to self-manage their fisheries, in terms of effort limitation and/or landing, were not accepted by the Dutch Authority for Consumers and Markets (ACM). Due to a lack of research, no ecological arguments for effort limitation were available and therefore any proposals by the industry to limit fishing effort and/or landings were deemed illegal price manipulations. Although the need for management was expressed by the industry, environmental NGOs, as well as scientists (ICES WGCRAN), the issue of management of brown shrimp fisheries was at a standstill. Therefore, IMARES was asked in 2011 by the Dutch sector to close the knowledge gaps and to determine if there is an ecological need for the management of the fisheries on brown shrimp in the North sea.

Firstly, the project aimed to facilitate the process of reaching international consensus on the possible ecological need for a common European management. To do so, IMARES prepared and participated in the ICES Workshop on the Necessity for Crangon “brown shrimp” and Cephalopod Management (WKCCM). The results were thereafter adopted by the Advisory Committee (ACOM) of ICES, leading to an official ICES advice stating that “the management of the *Crangon crangon* fishery in the North Sea would have benefits for the fishery in terms of sustainable yield and for the environment”. Furthermore, a harvest control rule, suggested by stakeholders and further refined based on science, was considered to be a good starting point for management. A roadmap was suggested to facilitate the possible implementation of this management approach. The ICES advice reflects the consensus among scientists that a management system for brown shrimp fisheries in the North Sea would be beneficial for both the ecosystem and the fishery. However, such broad consensus among the member states involved, the industry and other stakeholders is still lacking. The industry does have an interest to establish a management system because within the industry a tentative agreement exists that an Marine Stewardship Council (MSC) certification is needed. In order to obtain MSC certification, an effective management system to manage the fishery in line with the long term sustainable yield and with minimal ecosystem impact, is needed. Hence the industry is working on a self-management system. This is a challenging task because the fleet is diverse and relatively unorganized.

As the second part of the project, a model of the dynamics of brown shrimp and its fishery was constructed and analysed. The aim was to provide a scientifically sound ecological knowledge base for the exploration of management options for the North Sea brown shrimp fishery. A mechanistic approach was used for the model; the model for brown shrimp is a dynamic energy budget (DEB) model. The population dynamics are modelled using the physiologically structured population dynamics framework, and the fleet dynamics model uses an agent-based modelling approach. The mechanistic approach resulted in a model that is based on the processes which lead to observed patterns, rather than on the patterns themselves. The parameterization of the model has been derived independently, without any complex fitting or calibration to the system we aim to describe.

The model describes the shrimp population and fleet dynamics in the eastern coastal zone of the North Sea from the south of the Netherlands up to the Danish west coast. The zone is divided into nine areas, based on the spatial distribution of the shrimp fleet, estimated on the basis of VMS data. In the model, individual vessels follow a harvesting strategy based on catch results and movement costs. A combination of data analysis (VMS, Vessel Monitoring System) and consultation of representatives of the Dutch brown shrimp fishery was conducted to get a better understanding of the behaviour of fishermen. Based on this consultation, the fleet has been divided into ‘local’ vessels, consisting of fishermen which are predominantly active in a single area and more mobile vessels that may fish in all the areas. Each vessel is assumed to start fishing on Monday, but has an opportunity to stop fishing for the remainder of

the week if the catches fall below a threshold Landings per Unit of Effort (LPUE) value. Furthermore, of the entire local and mobile fleet, half of the vessels do not fish for shrimp between December and February.

The strongly mechanistic basis of the model and the independently established parameterization, coupled with good correspondence of the dynamics exhibited by the model to that observed, made that the model can be reliably used to estimate the effects of various management scenarios. Based on the consultation of representatives of the industry the following management scenarios were tested:

- The 2-step harvest control rule (HCR) which relies on a LPUE threshold value to trigger. When LPUE falls below 75% of this trigger value, Maximum total weekly time at sea is reduced to 72 hours. When LPUE falls below 50% of the trigger value, time at sea is reduced to 24 hours (Figure 16). This HCR criterion is evaluated on a weekly basis: LPUE is evaluated at the end of each week, and if it is below 75% or 50% of the trigger value, effort for the coming week is limited.
- Number of days at sea: in- or decreased with 2 days per week, from 5 to 3 days or 7 days fishing per week. Where 7 days is basically similar to the situation of no management at all.
- More/fever ships: in- or decreased by 200 vessels, from 500 to 700, or from 500 to 300 vessels
- Effort creep: increase the effective number of fishing hours per fishing day from 12 to 18.

We found clear indications that compared to the current situation, a reduced fishing effort will lead not only to a more efficient fishery (higher LPUE), but also to an absolute annual catch increase and reduction of discards of undersized shrimp. Such effort reduction is ecologically desirable because it is associated with reduced bottom disturbance, bycatch of non-target organisms, fossil fuel use and disturbance of other wildlife. Our results furthermore indicate that these ecological benefits will be obtained by implementing a harvest control rule for brown shrimp, and that these benefits go hand in hand with higher landings and a more efficient fishing fleet. While it is ecologically desirable to reduce impact, higher landings are not necessarily desirable from an economical point of view. Although reduced effort might result in lower cost, the higher landings will negatively affect shrimp prices, making it more difficult for individuals vessels to turn a profit. The current study indicates that the effort reduction can also be attained by reducing the number of vessels, and this will lead also to higher landings. However, these would be shared among fewer vessels.

The model developed in this study provides a suitable and versatile platform to study a large variety of alternative management scenarios, development in the fleet, gear innovations and environmental changes. In this study we have mainly focused on the effects of a Harvest Control Rule, as suggested in the ICES road map. However, the model can also be used to evaluate (the effectiveness of) other ways of management or a combination of measures. The model can hence play an important facilitative role in all future discussions regarding brown shrimp fisheries management in the North Sea. Given the importance of international (scientific) consensus, the results of this study will be presented and discussed during de next WGCRAN meeting in spring 2016. Furthermore the industry and IMARES have the intention to organise a stakeholder meeting in 2016 to discuss the results of this study and use them to continue the path towards a more sustainable brown shrimp fishery, here in the Netherlands and international.

1 Introduction

1.1 Background

Fisheries targeting brown shrimp (*Crangon crangon*) mainly occurs in coastal shallow areas of the Southern North Sea; the Dutch coastal area, the Wadden Sea and the Sylt area (Glorius et al. 2015, ICES 2013). The total North Sea fleet includes 523 (2011) to about 630 (2009) active vessels with two thirds of the fleet under Dutch and German flag. For years already there is a situation of overcapacity of shrimp fisheries in European coastal waters; increased landings of shrimp have led to sequential reduction of the shrimp prices (Taal et al. 2010). Fisheries targeting brown shrimp in the North Sea are largely unregulated in terms of landings and effort. As a result, there is no dedicated monitoring of the state of the shrimp stock, limited research into environmental impact, and little insight into the sustainability of the fishery (ICES 2013). The only European legislation on brown shrimp fisheries is focussing on technical measures (use of sieve net and minimum mesh size). Other management initiatives are local and include licences and closed areas, and in the Netherlands fishermen are not allowed to fish in the weekends.

In 2011 the shrimp fisheries experienced severe difficulties with the German, Danish and Dutch fleets striking for several weeks during spring because of extremely low prices offered by the processing and trading companies, and the industry perceived that the implementation of a prerequisite management plan would help (ICES 2011). However, a similar situation in the past has led to fines from the Authority for Consumers and Markets (ACM[1]) for the Producers Organisations (PO) and Wholesalers. In the late nineties the PO's and the Wholesalers response to the overcapacity in the shrimp sector was to agree on maximum landings per vessel. However, without ecological arguments for the measures at that point, the agreements were classified as price manipulative measures and thus illegal. Independently of the price issue fishermen organisations in the Netherlands, Germany and Denmark started a Marine Stewardship Council (MSC) assessment process to become MSC certified in 2007. An important prerequisite for MSC certification is that effective management of the targeted stock is in place. As an important step towards the implementation of management, the industry designed a self-regulation system based on landings per unit effort (LPUE) (the harvest control rule HCR (Temming et al. 2013)). Still, these agreements on fishing effort or landings made in the proposed management plans were not accepted by the ACM: due to a lack of research, no ecological arguments for effort limitation were available and therefor any proposals by the industry to limit fishing effort and/or landings where deemed illegal.

The issue of necessity for management of the fishery of brown shrimp was discussed within the ICES Working Group WGCRAN in 2011 (ICES 2011). Despite limited scientific knowledge, the WG was unanimous on the need for a management plan for the shrimp fisheries for the following reasons:

- Brown shrimp fisheries takes place in ecologically important nursery areas, using highly unselective gear as mesh sizes are amongst the smallest used (20 mm cod end) in any fisheries.
- It is unlikely that under the new Common Fisheries Policy the current situation of no management will persist.
- Most of the fisheries occur within Natura2000 sites and internationally recognised nature areas such as the Wadden Sea.
- In addition, the Dutch, German and Danish Wadden Sea has been assigned World Heritage Site status by UNESCO in June 2009. This recognition of global significance warrants the existence of a management plan for shrimp fishery in the area.

Although the need for management was expressed by the industry, environmental NGOs, as well as scientists, there was still a lack of consensus on this topic from governments, on national as well as European level. At this point the issue of management of shrimp fisheries is at a standstill.

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[1] The Netherlands Authority for Consumers and Markets (ACM) ensures fair competition between businesses, and protects consumer interests. See https://www.acm.nl/en/ for more information.

1.2 Research question

IMARES has been asked to gather data on shrimp & shrimp fisheries and develop new knowledge in order to answer the following question:
Is there an ecological need for the management of the thus far mainly unregulated fisheries on brown shrimp in the North sea?

1.3 Approach

The project aimed to close current knowledge gaps on the brown shrimp stock and ecology. The aim can be divided into the following two main objectives:

1. Facilitate the process of reaching international consensus on the possible ecological need for a common European management of North Sea brown shrimp fishing activities.
2. To provide a scientifically sound ecological knowledge base for such a management plan.

The activities of IMARES for objective 1 are described in chapter 2. The main activities of the 2nd objective were (chapter 3 onwards):

- Development of a population model for shrimp.
- Development of a fleet dynamics model to describe the behaviour of the fishing fleet under various management scenarios.

An important assumption underlying this work is that the magnitude of the potentially detrimental side effects of brown shrimp fisheries is closely related to fishing effort. The most important of these side effects are seafloor disturbance, mortality of non-target organisms (including bycatch) and fossil fuel use. This means that in this study, we interpret a reduced effort of the brown shrimp fleet as better in an ecological sense.

2 Governance and the process at ICES

The first objective of the project was to create international consensus on the possible ecological need for a common European management of the North Sea brown shrimp fishing activities. The most important activity for this objective was preparation of and participation in the ICES Workshop on the Necessity for Crangon "brown shrimp" and Cephalopod Management (WKCCM) which took place in October 2013. A direct output of this activity was the WKCCM report (ICES 2013).

A year later, in November 2014, IMARES participated in an Advice Drafting Group after which an official ICES advice was formulated stating that:

"ICES advises that the management of the Crangon crangon fishery in the North Sea would have benefits for the fishery in terms of sustainable yield and for the environment (taking ecosystem, mixed fisheries, and multispecies considerations into account)."

(full advice in appendix 1).

To understand the relevance of these activities in relation to the objective it is important to understand ICES and the role of ICES in the decision making process in European fisheries management. This is discussed in more detail in the following sections.

2.1 ICES

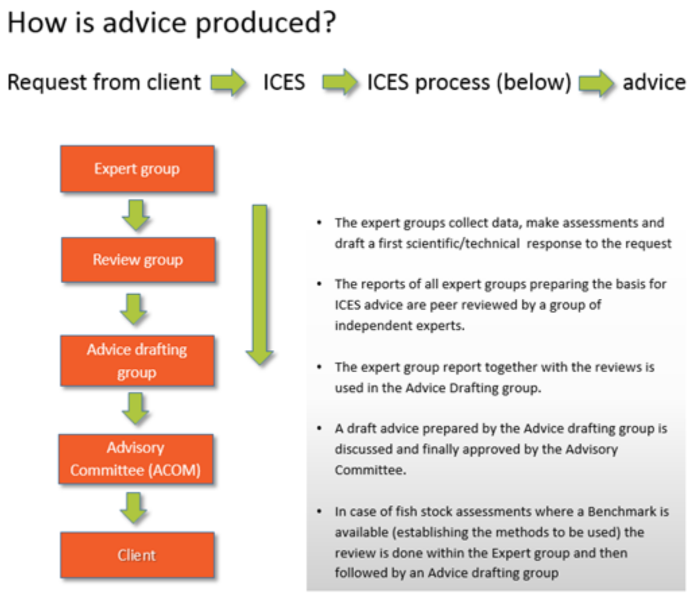
The International Council for the Exploration of the Sea (ICES) is a global organization that develops science and advice to support the sustainable use of the oceans. ICES has almost 150 expert groups and workshops that address the many diverse issues of the marine ecosystem. Expert group members work throughout the year and normally meet with their respective groups annually or bi-annually to work through a series of assigned tasks – known as Terms of Reference (ToRs). The ToRs are assigned by each group's parent committee, either the Advisory Committee (ACOM) and/or Science Committee (SCICOM) (www.ices.dk).

The Science Committee (SCICOM) is the main scientific body of ICES and oversees work in all aspects of marine science including ocean dynamics, climate variability and change, ecology and ecosystem function, survey and sampling, integrated assessment and modelling, fishery, aquaculture, and environmental science. The Advisory Committee (ACOM) is responsible for the provisioning of scientific advice to competent authorities in support of the sustainable management of coastal and ocean resources and marine ecosystems throughout the North Atlantic Ocean.

The ICES Working Group on Crangon fisheries and life history (WGCRAN) examines the various interactions of the brown shrimp to better understand the species. The group aims to improve understanding of the interactions between the brown shrimp population (structure and abundance) and human behaviour (mainly fishing effort) and between the shrimp and the environment (f.e. temperature, currents) as well as the ecosystem (trophic interactions). In the end a better understanding of the stock status will allow for sound advice for sustainable management of the population.

2.2 Management process

Despite the recognition by WGCRAN already in 2009 that there are reasons to develop a a management plan for this unregulated fishery, no official ICES advice was provided at the time. Following the official advisory route of the advisory process there is a need for a client (government) to request an advice (Figure 1).



- The expert groups collect data, make assessments and draft a first scientific/technical response to the request
- The reports of all expert groups preparing the basis for ICES advice are peer reviewed by a group of independent experts.
- The expert group report together with the reviews is used in the Advice Drafting group.
- A draft advice prepared by the Advice drafting group is discussed and finally approved by the Advisory Committee.
- In case of fish stock assessments where a Benchmark is available (establishing the methods to be used) the review is done within the Expert group and then followed by an Advice drafting group

Figure 1 ICES advisory process (www.ices.dk).

However, based on the WGCRAN suggestions, ACOM decided to organize a special workshop on the necessity of brown shrimp "brown shrimp" and cephalopod management (WKCCM). The WKCCM took place in October 2013 and focused on identifying whether a stock assessment is possible and whether management of brown shrimp fishery is necessary.

The terms of reference for WKCCM were as follows:

a) a) Provide advice on the need for management of *Crangon crangon* (brown shrimp) in the North Sea and cephalopod stocks[2] in the Northeast Atlantic, considering:
    i. The role of Crangon "brown shrimp" and cephalopods in the ecosystem and foodweb - specifically if they were considered low trophic level species;
    ii. The impact of the Crangon "brown shrimp" and cephalopod fishery on other commercially exploited fish stocks in relation to multispecies and mixed fisheries considerations;
    iii. The impact of the brown shrimp fisheries on Crangon "brown shrimp" and the cephalopod fisheries on cephalopods.
b) Develop a strategy and road map for the inclusion of Crangon "brown shrimp" and cephalopod fisheries data to be included in ICES multispecies and mixed fisheries assessments (where relevant); If a need or a potential need for a management of these currently unregulated resources is identified, then:
c) Develop potential steps towards a brown shrimp and/or cephalopod management, including due considerations of research needs and required stakeholder feedback.

WKCCM also concluded that there is a need for management. However, the *pro bono* advice in favour of management of brown shrimp fisheries, which the WKCCM participants hoped for, was not issued by ACOM. A *pro bono* advice is an advice ICES gives on its own initiative, and for which no formal request from a member state is required. This type of advice is generally conceived as a strong signal to the member states that action is required.

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[2] Fisheries of many cephalopods are of high regional economic and ecologic importance, and the majority of the fisheries is, as well as Crangon, so far only managed by some technical measures with little respect to environmental impact and sustainability of the fisheries. Therefor ICES has decided to combine both issues in one workshop. Within this project however we will not further discuss this issue as it is not within the scope of the assignment.

The results and conclusions of the WKCCM group did persuade the Dutch and the German government to file a request for advice on the necessity of management of the brown shrimp fishery. With this request an official advice on the management of brown shrimp fisheries became a fact.

In the advice, ICES also indicated how the management of the Crangon crangon fishery might be considered (appendix 1). Due to the short life span of brown shrimp an annual stock assessment and annual TACs are not suitable. Appropriate management would be needed to effectively limit the fishing effort, as reaching the maximum sustainable yield does not seem possible unless effort is reduced from the current level. A harvest control rule as suggested by stakeholders and further refined based on science is considered to be a good starting point for management. ICES suggests a 6-step roadmap to facilitate the possible implementation of this management approach. The steps of the road map include:

1. Data assimilation and evaluation of ?short-term research needs
2. Agreement on the design of HCR (definition of trigger values and effort reduction levels)
3. Development of a possible monitoring strategy
4. Test phase
5. Evaluation and adjustment of the HCR
6. Application and re-evaluation phase

3 The Dutch brown shrimp fleet

3.1 Methods

Two research methods were used to study the dynamics of the Dutch shrimp fleet: 1) data obtained from the Vessel Monitoring System (VMS) and electronic logbooks (hereafter: logbook) of the Dutch demersal fleet were analysed and 2) qualitative interviews were held with experts. These lines of research were pursued simultaneously, to maximally inform each other. First, VMS and logbook data analysis was conducted to get an impression of the distribution and the behaviour of the shrimp fleet. This VMS data analysis subsequently provided useful information that fed into the questionnaire that was developed for the interviews. Finally, the interview outcomes were used to further examine the VMS and logbook data. Visual inspection of the spatial distribution of VMS positions of shrimp trips over time (per quarter for 2010-2013 was used to determine main fishing grounds applied in the model (§4.1.1).

3.1.1 Processing & analysing vessel monitoring system (VMS) and logbook data

VMS and logbook data were received from the Dutch Ministry of Economic Affairs and stored in a local database at IMARES. The data was transformed into the 'VMS' and 'logbook' format for VMS and logbook data respectively to aid analysis. The methods used to analyse VMS and logbook data are standardized and agreed upon with partner institute LEI and the fishing industry (Hintzen et al. 2013).

Logbook data

All European fishermen are obliged to report their activities on a daily basis. This includes location, gear used, vessel characteristics and estimated landing quantities (in kg). These quantities are an estimation and therefore deviate from auction data. With using this data one needs to consider the following issues:

- Fishermen do not have to report catches at species level when a trip-total quantity is below 50 kg. Moreover, the reported catches are estimates made by the fishers. Auction quantities may therefore deviate a little.
- Fishermen report all landings and vessel characteristics online and the data are immediately imported in the database of the Dutch Government. IMARES performs some checks on this data, but is unable to recognize all wrongly entered input, such as type-errors in gear description. Consequently, it is possible that the dataset used contains incorrect records due to type-errors.

VMS data

All ships over 12 meters length are obliged to participate in the Vessel Monitoring System (VMS). This system sends an update to a satellite every two hours, containing time and date, position, speed and name of the vessel. All these records are registered by the Dutch government. IMARES has permission to work with these data.

Link VMS and logbook data

VMS and logbook datasets were linked using the unique vessel identifier and date-time stamp available in both datasets. In other words, records in the VMS dataset that fall within the departure-arrival timeframe of a trip described in the logbook were assigned the unique trip number from the logbook record which allows matching both datasets. Multiple active fleet segments were determined, based on gear type, mesh size, and engine power, resulting in 16 different fleet segments (Table 1). These fleet segments include both active trawling gears as well as passive gears such as gill and trammel nets, longlines, pots-fisheries, handlines and other gears.

Table 1. Definitions of the active fleet segments as used in VMS and logbook analysis. (TBB: Beam Trawls, TBS: Beam Trawls brown shrimp fisheries, OTB: Otter Bottom Trawls, OTT: Otter Twin Trawls, SSC: Scottish seines, SDN: Danish seines, DRB: Boat Dredges, HMD: Mechanical (suction) Dredges, PTB: Paired Bottom Trawls, OTM: Otter Midwater Trawls, PTM: Pair Midwater Trawls.)

Fleet segment	Gear type	Mesh size (mm)	Engine power (kW)
TBB225	TBB	>32	0 – 225
TBS225	TBB	15 – 32	0 – 225
TBB10000	TBB	> 32	>= 225
TBS10000*	TBB	15 – 32	>= 225
OTB225	OTB	All	0 – 225
OTB10000	OTB	All	>= 225
OTT225	OTT	All	0 – 225
OTT10000*	OTT	All	>= 225
SSC500	SSC, SDN	All	0 – 500
SSC10000	SSC, SDN	All	>= 500
DRB500	DRB	All	0 – 500
DRB10000	DRB	All	>= 500
HMD	HMD	All	All
PTB	PTB	All	All
OTM	OTM	All	All
PTM	PTM	All	All
* These fleet segments had a limited number of registered trips and were therefore merged with another fleet segment. In case of TBS10000, trips were merged with TBB10000; trips of OTT10000 were merged with OTB10000.			

Define fishing activity

Speed recordings obtained from VMS data were used to create frequency plots of these speeds, where along the horizontal axis the speed in knots is given and the vertical axis denotes the number of times that speed was recorded. In general, 3 peaks can be distinguished in such a frequency plot: A peak near 0 knots, associated with harbour/floating; a peak around the average fishing speed (3-3.5 knots); and a peak around the average steaming speed (8-9 knots). Using the frequency plots, activity is determined for each VMS-point based on the speed recorded. Activity analyses were performed separately for each fleet segment.

Creating base data files

From the linked VMS and logbook data, two base files were created to perform the analysis. The first base data file only contained data of the shrimp fleet segment (TBS225) over the years 2010-2013. The second base file consisted of data for all fleet segments over the years 2011-2014. Each base file is an overview with all unique VMS-positions of the trips for which logbook data was available, and which were determined as ‘fishing’ based on speed. The fishing effort determined from the logbooks (in kWdays) and the landings recorded in the logbooks (in kg) were assigned to each VMS record. In the Netherlands 2 types of licences exist for shrimp fisheries. The GV licence is valid in all coastal areas except the Wadden Sea and the GK licence is also valid in the Wadden Sea. Based on a list obtained from the ministry, licence type could be assigned to each vessel.

3.1.2 Behavioural variation in spatial distribution of the fleet

Based on VMS and logbook data quarterly effort distribution maps were made. In addition, the yearly average number of different arrival harbours per vessel were calculated over the period of 2010-2013. In this calculation only vessels with more than 10 shrimp trips in a year are considered.

The next analysis on fishermen’s behaviour aimed to test whether the choice of fishing area was based on the catches of the previous week. To do so, the assumption was made that every fisherman knows all catches and corresponding fishing grounds in a given week. Based on VMS positions, each trip was assigned a fishing area corresponding with the fishing areas determined to use in the model (§4.1.1). Trips with VMS locations in multiple fishing areas were removed, as were trips that lasted longer than 1 week. Multiple trips of a vessel within a week were considered 1 trip. Total shrimp revenue (in euro per kWday) was calculated for each fishing area per week, by dividing the total shrimp profit (euro) in the fishing area by the total fishing effort in that fishing area for each week. For each week, the difference in revenue between the used fishing ground and the other fishing areas was determined and linked to each trip. When two consecutive fishing trips were performed in different fishing areas this was defined as a "shift". This resulted in a dataset with for each trip the current fishing ground, the previous fishing ground of that vessel, a column indicating whether a vessel has shifted to another fishing area and, if so, the revenue difference between the two fishing grounds in the previous week. From this, we calculated how many times a vessel had shifted fishing ground, and how often this shift was possibly based on higher expected shrimp catches.

3.1.3 Varying target species

Not all shrimp fishers target shrimp year round as some have the option to switch to Nephrops and/or sole fisheries. The extent and seasonal pattern of these "switchers" was analyzed by using the base file of 2011-2014 with all gears.

For this analysis all trips with at least 1 recorded shrimp fisheries trip were selected and gear types were assigned. Gear types were classified as shrimp (TBS225), tbb (TBB225), otb (OTB225 & OTT225), or other (see Table 2 for definitions of fleet segments abbreviations). Based on anecdotal knowledge, the assumption was made that beam trawls with larger meshes (TBB225) are targeting sole and small otter trawlers (OTB225) are targeting Nephrops. For each vessel, the percentage of employment for the four gear types was calculated and with these percentages, all vessels were assigned to one of the following 8 fishing gear groups: shrimp_only, shrimp_tbb, shrimp_otb, shrimp_gn, tbb_shrimp, otb_shrimp, gn_shrimp and abberant.

3.1.4 Interviews

Semi-structured interviews were conducted with representatives from the shrimp fleet about the fishing behaviour of Dutch shrimp fishers. Semi-structured interviews are flexible, qualitative interviews during which the interviewer ensures that a list of topics is discussed, but the order is not predetermined. Respondents get the time they need for their reply and it is possible for the interviewer to elaborate further on the answers of the respondents. This form of interviewing is suitable to get rich information and allows for unexpected issues to be brought up and discussed further.

The list of interview questions was established on the basis of conversations with the modellers and informed by the results of the first VMS and logbook data analysis. In these conversations the modellers were asked what information they needed for the model about the behaviour of the Dutch shrimp fleet and which ideas they already had about this behaviour. The questions and assumptions of the modellers were formulated into a list of questions to be asked to experts of the Dutch shrimp fisheries (see appendix 2 for the interview guide).

Fishermen, representatives of producer organisations and interest group leaders were approached as experts of the Dutch shrimp fisheries. The respondents were selected based on their extensive experience in shrimp fisheries and because it was assumed that these people would be knowledgeable on the general behaviour of the fleet, which is more relevant for the purpose of this research than individual behaviour of single fishermen. It was ensured that representatives from different important shrimp communities in the Netherlands were interviewed to get inside information about different groups of shrimp fishers. Another way of collecting data about the general behaviour of the Dutch shrimp fleet would be to hold structured questionnaires among a large number of shrimp fishers. The time and means that were available did however not allow for such a more time consuming approach. In addition, the advantage of qualitative interviews in comparison to structured questionnaires is that the qualitative interview method better allows for unexpected answers to be given by respondents.

Eight shrimp fisheries experts were interviewed between May and June 2015 and informal conversations about shrimp fisher behaviour were held with a shrimp fisher and his crew member during a field trip on a shrimping vessel. Five of the respondents were interviewed individually for approximately an hour and three of them in a group interview, that lasted three hours. The interviews were recorded, transcribed and analysed on the basis of the topics that were important for the modellers. It should be clear that the results from the interviews are generalisations that always have exceptions. However, the information is of value to improve the validity of the modelled fleet dynamics.

3.2 Results

3.2.1 Behavioural variation in spatial distribution

The quarterly spatial distribution of the Dutch fleet showed seasonal patterns (see appendix 3), with a shift in activity from the South of the Netherlands at the end of summer towards the Sylt region during winter. On average, vessels arrived at 3.2 unique harbours per year (Figure 2). However, differences in number of arrival harbours can be observed between vessels, with the majority of the vessels arriving at a lower number of unique harbours per year (60% of the vessels with 1.75 harbours on average), and the remaining vessels arriving at up to 9 different unique harbours per year on average (40% of the vessels with 5.40 harbours on average).

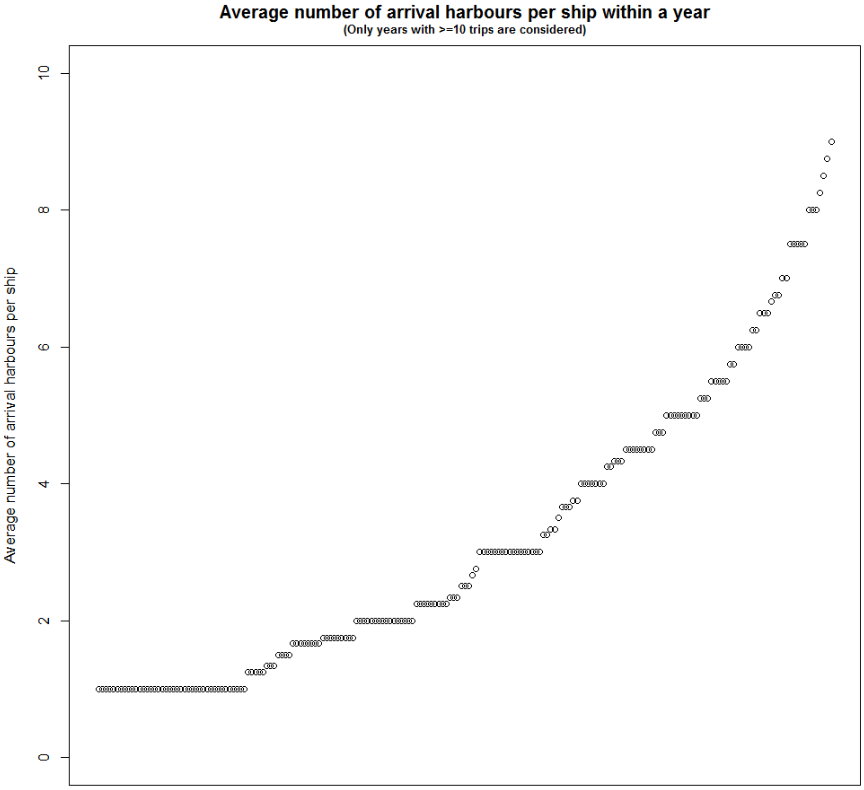

Figure 2 Average number of arrival harbours per vessel within a year for the Dutch brown shrimp fleet. This includes arrivals in harbours without an auction and international harbours. The x-axis represents the shrimp vessels, sorted according to the number of arrival harbours.

The data in Figure 3 show the revenue per unit effort (VpUE) difference for all location shifts (3A) representing all shifts to new fishing areas, and average VpUE differences of all shifts per vessel (3B). The y-axes represents the (average) difference in VpUE between the current and new location. Hence, a positive difference represents a shift towards an area with higher revenue than the current fishing location. This data shows that vessels shift between locations in such a way that on average, they move towards areas of higher revenues.

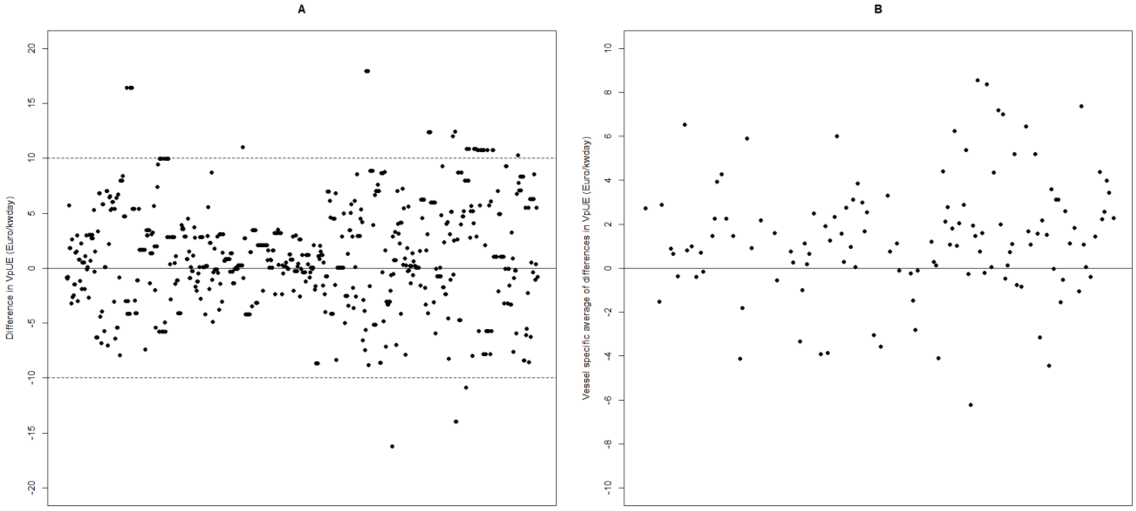

Figure 3. Revenue difference for all location shifts (3A), representing the difference in VpUE for each shifts to a new fishing area and the vessel specific average difference in VpUE for all shifts per vessel (3B). The x-axis represents all shifts (left) and vessels (right) in the order in which they occur in the data.

3.2.2 Varying target species

The majority of the shrimp fishermen are solely targeting shrimp (Table 2). However, part of the fleet is composed of shrimp fishers that –for some time of the year– employ different fishing gears, so-called “switchers”, and presumably target sole (TBB225) or Nephrops (OTB225). The majority of these “switchers” predominantly target shrimp. Only a limited number of vessels is employing other gears than shrimp, tbb or otb (Table 2 “abberant”).

Table 2. Definitions of fishing gear groups

Fishing group	**Definition**	**Number of vessels**
Shrimp_only	≥95% of the trips is TBS225	142
Shrimp_tbb	≥50% of the trips is TBS225, ≥5% of the trips is TBB225	18
Shrimp_otb	≥50% of the trips is TBS225, ≥5% of the trips is OTB225	15
Shrimp_gn	≥50% of the trips is TBS225, ≥5% of the trips is other	3
Gn_shrimp	<50% of the trips is TBS225, ≥50% of the trips is other	1
Tbb_shrimp	<50% of the trips is TBS225, ≥50% of the trips is OTB225	9
Otb_shrimp	<50% of the trips is TBS225, ≥50% of the trips is TBB225	6
Abberant	All remaining trips	4

3.3 Interviews

This section constructs the dynamics of the shrimp fleet based on the information obtained from the respondents.

3.3.1 *Supply of shrimps throughout the year*

The fleet dynamics vary throughout the year. The main shrimp season is at the end of summer and at the beginning of autumn. After this season the shrimps move to deeper waters and mainly the relatively large boats continue fishing for shrimps in the Sylt area. From January till Easter the shrimp fleet is the least active, in particular the smaller vessels remain in the port because they cannot reach the deeper areas where the shrimps are. According to the shrimp fisheries representatives the shrimp fishers start fishing more intensively already from July onwards, awaiting the shrimp season. Shrimping is good in coastal waters at the end of summer/in early autumn, not only because the increased/high density of the shrimps but also because the water is more cloudy than before, caused by windy weather and longer nights, which increases the catchability of the shrimps. In the Wadden Sea the water is always cloudy, so in summer, the catchability in the Wadden Sea is better than in the other coastal waters, provided that there are shrimps.

3.3.2 Different groups of shrimp fishers

The respondents were asked to what extent they can distinguish between different groups of fishermen within the shrimp fleet, when looking at fisheries behaviour. All respondents could distinguish groups, based on various factors that influence fisheries behaviour. The following factors were mentioned to distinguish groups in the Dutch shrimp fleet:

- The size of the operation, in terms of the number of crew members or the economic size of the company, is the first factor that was mentioned to be of importance for fishing behaviour. For instance, when there are more crew members, a greater landing revenue needs to be realised to pay the crew. Similarly, when the shrimping company has large loans, the pressure is higher to realise a high landing revenue. Length of the ship is not considered a good factor to distinguish between groups by the respondents. The respondents answers concerning vessels' engine capacity as important differed and engine capacity was therefore not considered.
- Searching behaviour and skills at sea is the second factor that was mentioned as a basis to distinguish groups. One respondent refers to this division as the difference between *knowledge fishermen* and *hours fishermen*. The *knowledge fishermen* do not need as many hours to realise a good revenue as the *hours fishermen*. The *knowledge fishermen* depend on their knowledge during fishing, while the *hours fishermen* depend more on the luck to find something. The skills of the *knowledge fishermen* are possibly based on talent, knowledge from their fathers and grandfathers and because they pay more attention to circumstances such as wind direction, water temperature, season, etc. Everybody in the community knows who the *knowledge fishermen* are. The respondent estimates that one third of the shrimp fishers are *knowledge fishermen* and the rest are *hours fishermen.* This division is relevant for management, as *hours fishermen* would most likely be more resistant against measures that limit days at sea or hours at sea, because they depend on the time they are fishing for their revenue.
- A third factor dividing Dutch shrimp fishermen in specific groups is the type of license. GV-license holders have the right to fish for shrimps in coastal waters, but not in the Wadden Sea. A GK-license in theory allows for shrimping in both the Wadden Sea and in the coastal waters. In practice the ships of GK-license holders need to be declared seaworthy by the shipping inspection to legally have permission to fish in the coastal waters outside of the Wadden Sea[3].
- A fourth factor that is considered as a basis to distinguish groups is the target species. A 100% shrimp fisher may behave differently than a fishermen who can also fish for other species as the former completely depends on the shrimp fishery. The size of the fishing fleet that only targets shrimp in a calendar year differs between years, with a larger fleet when conditions are in favour of shrimp fisheries and a smaller fleet when conditions are in favour for other species. Fish and shrimp market prices, quota rent prices, and the availability of target species are important factors that influence the shrimp fisheries conditions.
- The fifth factor on the basis of which groups can be formed is the home port of the fishers. Fishermen from the same home port often show similar behaviour. Other factors mentioned above (the first, third and fourth) can to a certain extent coincide with this factor. In addition,

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[3] According to Keus and Jager (2008) in 2008 128 of the total 215 shrimping license holders had a GV-license, and 87 of them had a GK-license.

the division of shrimp fishermen on the basis of home port is relevant, because home port determines to a certain extent the fishing areas. This division will be further elaborated below.

3.3.3 Group formation based on home port

If the Dutch shrimping fleet would be divided into groups based on home port, four groups can be distinguished according to the respondents: The South, Den Oever, Harlingen & Lauwersoog and Urk. Table 3 shows the respondents' estimates of the number of fishermen in each group[4]. The table also contains an estimation of the number of foreign shrimp fishers that fish in Dutch coastal waters, including Dutch fishermen fishing under a foreign flag.

The South (in Dutch: de Zuid) includes the harbours in the province of Zeeland and the harbour of Scheveningen. The shrimp fishers belonging to these harbours are mainly euro cutters[5], which are relatively large vessels for shrimping. Besides shrimp, these fishermen often target sole. These fishermen generally prefer to fish for sole, but high shrimp abundances nearby or high rent prices for sole quota form reasons to switch to shrimp. Most southern shrimp fishermen do not go further north for shrimp fishing than Ijmuiden, but some go north to the Sylt area in winter. The southern fishermen generally stay at home during the weekend.

The harbour of *Den Oever* is home to fishermen that are a member of the PO Wieringen. The Wieringen shrimping companies on average have a larger financial size than shrimping companies in the other groups and higher loans, because Wieringen fishermen invest and innovate more compared to fisherman in the other groups. This results in a need for higher revenues, which drives fishermen to make more hours at sea. At least a quarter of the Wieringen fishermen switch from shrimps to Nephrops in summer.

The northern harbours of *Harlingen* and *Lauwersoog* are the homes to a fleet with relatively small and old ships. In Harlingen, Lauwersoog and its surroundings less investments are made to renew shrimp vessels than in Wieringen. One representative formulates the difference as follows: '*One celebrates the hundredth anniversary of his vessel, the other says he would rather get a new vessel*'. Having less loans results in a reduced necessity to fish for maximum catches to pay back loans. Fishermen from these harbours thus in general accept to be fewer days at sea (although *Lauwersoog* also has some larger shrimp vessels with a GV-license).

The number of shrimp vessels from *Urk*[6] varies. According to one representative, the number of Urker shrimp vessels had risen since the good shrimp years of 2012 – 2013. Based on experience, this representative expects that after two or three poor shrimp years, the number of Urker shrimping vessels will decrease again. The Urker shrimp fishers vary easily between harbours and fishing areas.

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[4] The group of fishermen from the Dutch islands, of which Texel is one, is not be discussed separately in the text, as it is a relatively small group compared to the other groups and it was not specifically mentioned as a separate group by the respondents.

[5] Euro cutters are cutters that have a length below 24 meters and a maximum engine capacity of 300 hp.

[6] Urk is an important fisheries community in the Netherlands. Since the *Zuiderzee* was closed off however with a dyke to form the *Ijsselmeer,* the village no longer has a marine harbour. The Urker fishermen have their ships in other harbours to which they commute by car.

Table 3. Estimations by the respondents of the number of ships per home port

Port	**Number of active vessels**	**Number of vessels with GK-license**	**Switch to other target species**	**Remarks**
The South	30	0	Majority	Switch to sole
Den Oever	40	30	25% switches actively, 50% has the possibility	Switch to Nephrops
Harlingen	30 (5 non-active)	35	Majority does not switch	
Lauwersoog	50	25	Majority does not switch	
Urk	15-20	0	Majority does not switch	
Texel	7	0	Majority does not switch	
Foreign vessels fishing in Dutch coastal waters	20	0	Unknown	Ca. 50% Belgian and 50% German flag

3.3.4 Foreign vessels

The respondents estimated that ca. 20 foreign vessels fish for brown shrimp in Dutch coastal waters, including Dutch fishermen that fish under a foreign flag. They estimated that approximately half of these twenty vessels are German and half of them Belgian. Fishing vessels from the two nations are subjected to different rules when fishing in Dutch coastal waters. Because of the Benelux treaty, Belgian vessels can fish up to the coast while German vessels cannot fish in the first three nautical miles off the Dutch coast. A frustrating issue for Dutch fishermen is that these foreign vessels are not bound by the weekend stop. How often foreign vessels fish for shrimps in Dutch coastal waters was not discussed. The interviews focussed on the Dutch fishing fleet, the behaviour of the foreign vessels was not further explored.

3.3.5 Varying target species

Roughly stated, the most important target species besides shrimp are sole and Nephrops; with a switch to sole mainly by fishermen from the South while fishermen from Den Oever mainly switch to Nephrops. Fishermen with a GK-license, who fish in the Wadden Sea, do in general not switch to other target species. Whether and when the shrimp fishers switch to a different target species depends on the market and quota rent prices for fish, Nephrops and shrimp and on the availability of the target species. This means that in a year during which shrimps are abundant and shrimp prices high, less fishermen switch to a different target species, compared to a year in which landings and/or prices are low, resulting in varying percentages of total Dutch shrimp fleet that switches to alternative targets.

For the fishermen that switch to sole, also the rent price of sole quota plays a role in their decision to switch between target species. When the quota rent price of sole is high, it is likely that less fishermen will switch to sole fisheries. Some of the shrimp fishermen that own fish quota, never switch to the species they have quota for, but they rent out the quota to others.

3.3.6 Fishing location

The respondents indicated that the following factors play a role in determining where shrimp fishermen will fish:

- The home port is important. There is a limit to the distance that can be travelled because fishermen have to be back in port again on Friday at noon because of the weekend stop in the Netherlands. In German waters the weekend stop does not apply and fishermen can thus fish longer in those waters.
    - Fishermen from the South largely remain in the Belgian and southern Dutch coastal waters. They follow the arrival of shrimp, which occurs in July in the south, and move North following the peak in shrimp abundance. When the fisheries are particularly good, they travel north up to Den Helder.

    - Fishermen from Den Oever fish almost everywhere (Wadden Sea if they have the license for it and also in the other coastal waters), with the exception that they do generally not cross the *Nieuwe Waterweg*[7] into southern coastal waters.
    - Those fishermen with a Wadden Sea licence generally have smaller vessels and crews and therefore fish closer to their home ports, which means that fishermen from Den Oever and Texel fish in the western part of the Wadden Sea, fishermen from Harlingen in the middle and fishermen from Lauwersoog in the eastern part. Wadden Sea fishermen often have fixed areas where they fish. On the one hand because the constantly changing Wadden Sea requires knowledge of the area. On the other hand because a sort of silent division of areas exists. The larger vessels leaving from Lauwersoog with a GK-license will generally travel eastwards.
    - Urker fishermen fish everywhere where shrimping is expected to be good.
- As discussed above, the type of license and the seaworthiness of the vessel determines where the fisherman can fish (GK-license permits fishing in the Wadden Sea and coastal waters and the GV-license only to the coastal waters).
- When there is little shrimp to be caught, the behaviour of the fleet is least predictable. Fishermen may travel far to search for shrimps and when good shrimp catches are made in a certain area, the movement of fishers to this area will be extra strong. This effect of fishermen being drawn to the same good fishing spots, is less evident in times when shrimping is good at the usual fishing grounds.
- Fuel price is considered of low relevance for deciding the fishing area because fuel consumption is relatively low in shrimp fisheries.
- Seasonal variation is important in the movement of the shrimp fleet. In winter, when the shrimps go to deeper waters (for instance the Sylt area, the German Bight), part of the fleet that is equipped for the deeper waters will follow the shrimp. The estimation is that 50-70 vessels on average fish in the Sylt area in winter. The largest share of vessels that fish in the Sylt area are from Den Oever. The period that most Dutch vessels fish in the Sylt area is between January and April.
- In case of stormy weather, fishermen will most likely go to areas in the lee of the coast.

3.3.7 The end of the fishing trip

The weather is considered the most important factor for determining whether fishermen will go out fishing or not after the weekend. When shrimp catches are poor, and the expectation is that the costs will exceed the benefits, some fishermen will stay in the port but most will go out anyway. The rationale is that they at least want to give it a try, and if results are disappointing, they can return earlier.

Once at sea, shrimp fishermen will aim to catch as much as possible because there is no limit to the amount of kilos that can be landed. The length of the fishing trip varies between the groups of fishermen. The Dutch shrimping week starts on Sunday night/Monday morning at 00:00 and ends on Friday at 12:00. Harlingen fishermen are usually back in the harbour on Thursday, while fishermen from Den Oever will arrive just before Friday noon. In the Sylt area and in the German Bight, shrimp fishing can be continued for nine days during a period of fourteen days. Some fishermen, mainly the ones from Den Oever, use this opportunity to fish for two periods of nine days in a row. Fishermen from the South and from the north eastern harbours will most likely choose to be home during the weekend.

Poor catches may be a reason to end the fishing trip earlier. According to one respondent, this is mainly the case in early summer when shrimps are less abundant. At the end of summer or beginning of autumn, fishermen will most likely continue in case of poor catches because there is a higher chance that areas with better catches will be found during the course of the week.

The shrimp trading companies are at times a reason to stop the fishing trip earlier. It has occurred, in periods of high shrimp landings, that trading companies decided to organise shrimp auctions on Wednesdays only, meaning that the vessels had to be back in the harbour at that time.

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[7] The canal at the height of Rotterdam, connecting the port of Rotterdam to the North Sea.

3.3.8 Arrival harbours

We asked the respondents to respond to the following statement: *"Fishermen who arrive in many different ports throughout the year switch between fishing areas based on their expected shrimp catches, whereas fishermen who visit a small number of ports act out of habit, and do not base their decisions on expected landings."* Three respondents replied that the assumption could be true, but they and the other respondents placed some critical remarks with this assumption:

- Arriving in various harbours can also be explained by vessels that land their catches in the most nearby harbour when the vessel storage is full. This practice especially occurs in summer when temperatures are high and is practiced by fishing vessels that fish for nine days in the Sylt area or in the German Bight. Several different harbours can be visited during a nine day trip;
- A large number of arrival ports does not necessarily relate to high mobility to places where high catches are expected to be found, and a small number of arrival harbours does not necessarily relate to 'going to the same fishing areas out of habit'. Fishermen fishing in the Sylt area may do so out of habit, while visiting many different nearby ports, while fishermen fishing in a small area may, on a small scale, vary fishing location based on expected catch and still always visit the same harbour.
- Other reasons to vary between harbours are for instance to bring the vessel to the dock, or vessels that land their catch in a different harbour than their home harbour.

In order to further test the assumption given above it is necessary to examine which harbours are visited by the vessels and whether there is seasonal variation in the number of harbours visited (i.e. a higher number of arrival harbours in summer because catch is landed more often before the end of the trip).

3.3.9 Management scenarios

The respondents were asked which management scenarios they would like to see tested in the model. Initially some respondents stated that adequate shrimp management is not possible because shrimps are so unpredictable, but during the course of the interview every respondent would at some point agree that a decrease in fleet shrimp capacity would be desirable. The following scenarios were mentioned as interesting to test in the model:

1. The MSC scenario, whereby fishing effort is restricted when landings per unit effort are below a certain standard;
2. Scenarios in which effort is steered on the basis of either fishing hours, fishing days or kilo's;
3. A scenario in which the weekend stop applies to the entire European brown shrimp fishing fleet;
4. The extension of the weekend stop to more days;
    a. While simultaneously abolishing the weekend stop in winter (this is desirable because this offers more flexibility in case of bad weather conditions);
5. A decrease of the European fleet by 25%, from ±500 to ±375 shrimp vessels.

Some respondents came up with scenarios with less regulations that could be helpful to convince others that management is needed:

6. The abolishment of the weekend stop;
7. An increase of the European brown shrimp fleet;
8. A transition of the fleet to pulse fishing (increase in efficiency).

3.4 Conclusions

This chapter reported on the two research methods, VMS and logbook data analysis and qualitative interviews, to study the behaviour of the Dutch shrimp fleet as input for the model.

From the VMS analyses the following conclusions can be drawn:

- The majority (60%) of the vessels of the Dutch brown shrimp fleet are relatively home bound and do not often switch their landing harbour.

- ➔ This led to the assumption that vessels with high number of unique arrival harbours were following the shrimp and fishing at locations with the highest expected catches, whilst the vessels with few unique arrival harbours have fixed fishing-grounds and do not move to locations with higher expected catches.
- Based on average revenue difference determined per vessel, evidence was found that the vessels switching fishing location based this decision on expected shrimp catches.
- Most fishermen (~70%) are solely targeting shrimp. However, some fishermen switch to other gears, in particular to beam trawls with larger mesh sizes (~10%) or otter trawls (~8%), targeting sole and Nephrops respectively. This is observed most from January to July.
- Shrimp fishermen mainly employing non-shrimp gears (~8%) may decide to target shrimp for various reasons. This is observed most in autumn (tbb to shrimp) and in winter (October to May; otb to shrimp).
- Largest fishing activity of shrimp fisheries is in the 2nd half of the year.

From the qualitative interviews with shrimp fisheries experts the following conclusions can be drawn:

- In the context of fisheries behaviour shrimp fishers can be divided in four groups based on home port: South, Den Oever, Lauwersoog/Harlingen and Urk.
- Home port is important for the fishing location of the fishermen, and the fleets of the different ports roughly differ from each other in vessel size and in species that are targeted besides shrimps.
- Trip length is mainly affected by weather conditions, and actual and expected shrimp catches.
- The choice for target species is determined, among others, by availability of the gear, fish price, quota rent prices and expected and realized catches.
- Whether there is a relationship between number of arrival harbours and fishing behaviour remains unclear.

3.5 Additional analyses

After the interviews a more precise estimate of fishing activity per season was wished for. With the VMS data the seasonal variation of gear type employment in the different fishing gear groups within the shrimp fisheries over 2011-2014 was plotted (Figure 4). Fishing activity of shrimp fisheries is lower at the beginning of the year, with a doubling of average number of fishing trips per week during the second half of the year. Switches to Nephrops (otb), sole (tbb) or other fisheries are observed all year round but peak around the second quarter. Non-shrimp-fisheries switching to shrimp do so mainly in autumn to winter and in spring. Aberrant vessels consist of vessels targeting shrimp in autumn but employ both tbb and otb gears during the rest of the year.

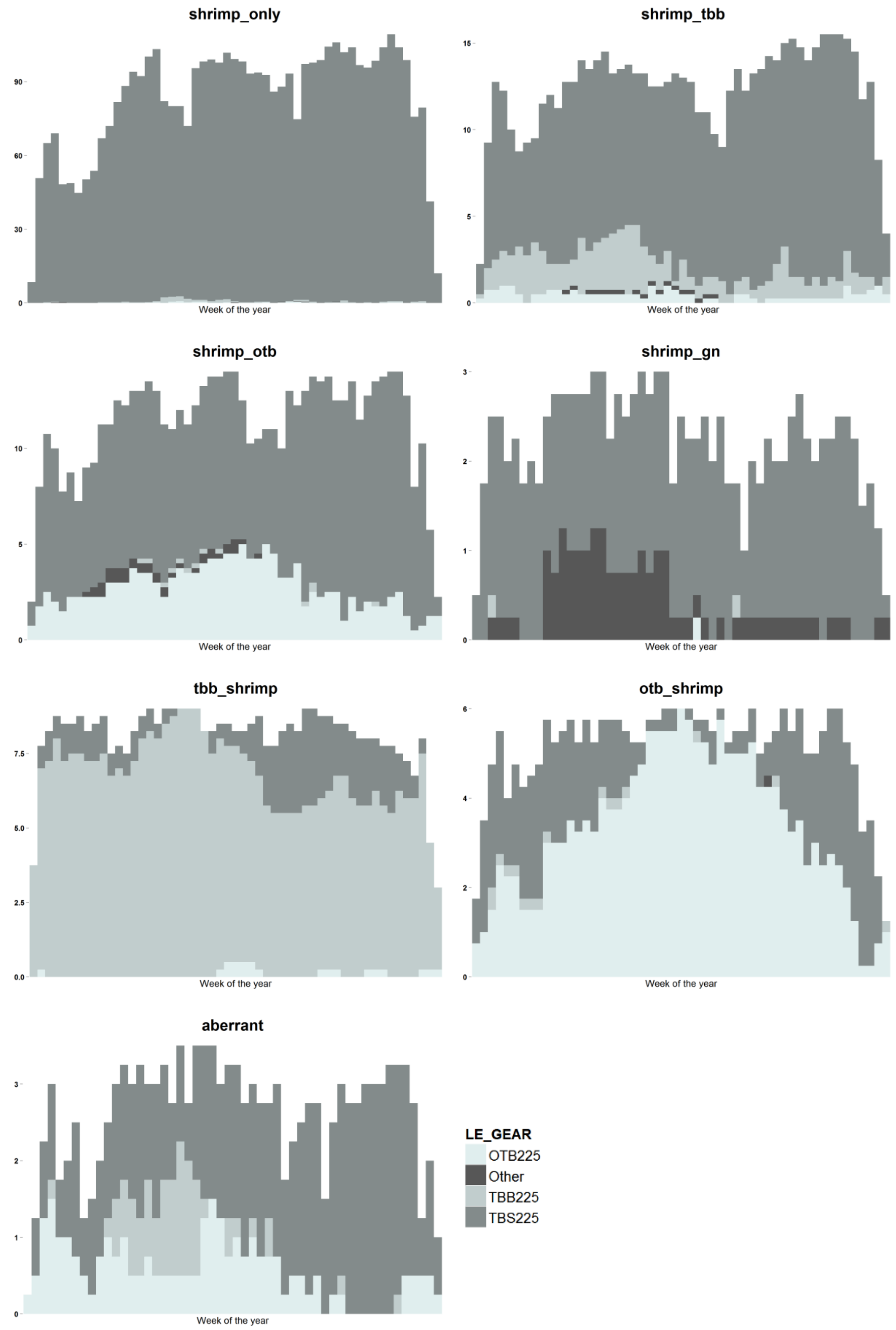


Figure 4. Seasonal variation of gear type employment in the different fishing gear groups within the shrimp fisheries over 2011-2014. On the Y axis the average number of trips for that week in a year is given, the X axis represents the weeks over the year starting with week 1 in January.

4 Model description

4.1 Methods

4.1.1 *Area definition on the basis of VMS*

As described in Chapter 3, the spatial distribution patterns of VMS positions of shrimp trips over time (per quarter for 2010-2013) were used to determine main fishing grounds applied in the model (Figure 5).

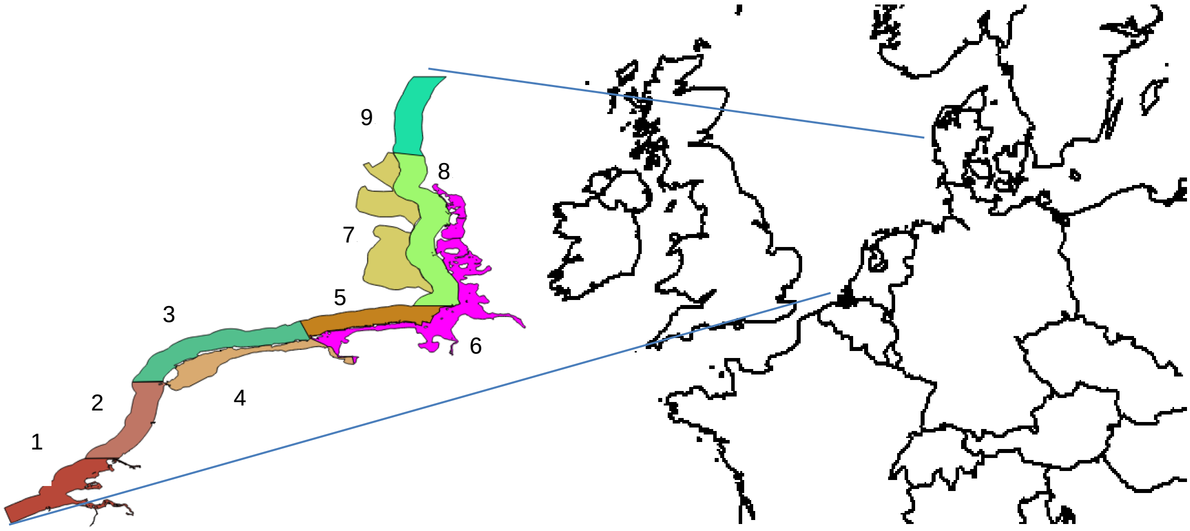


Figure 5. The geographical extent of the model along the Dutch, German and Danish coast in the southern part of the North Sea. On the right the location of the area with Western Europe as reference. Each area, as indicated by a number, consists of a shallow and deep region. See Table 4 for other properties of the areas.

Table 4: Environmental properties of areas used in the model

Number	**Name**	**Abbreviation**	**Surface (ha)**	**Temperature parameters**			
				amp	center	offset	width
1	Dutch Delta	DeltaNL	34185	7.4777	135.9978	284.0478	182.4366
2	Dutch Westcoast	wcNL	28771	7.3358	139.8807	283.9741	182.4294
3	Dutch North Coast	ncNL	41067	7.0438	140.5430	283.6125	182.4199
4	Dutch Wadden Wea	wadNL	25892	8.2148	119.2848	283.4544	182.4888
5	German North Coast	ncD	28166	7.5997	136.4769	282.9087	182.4844
6	German/Danish Wadden Sea	wadD	58305	8.6653	121.6070	283.1138	182.5169
7	German West Coast	wcDK	58760	6.9412	144.6496	282.4920	182.4324
8	Sylt	Sylt	60803	6.6879	146.8205	282.5322	182.4150
9	Danish West Coast	ncDK	28311	6.9412	144.6496	282.4920	182.4324

4.1.2 *Model Assumptions*

This model uses the Escalator Boxcar Train (EBT) concept (DeRoos et al. 1992) to model cohort dynamics including individual level processes and their environment consisting of a resource and a fishing fleet. The core of the EBT model are the individual level processes. The individual level processes are modelled using a Dynamic Energy Budget (DEB) model parameterized for brown shrimp (Campos et al. 2009). DEB models are based on first principles of energy flow within an individual, from energy uptake, distribution of energy to soma and reserves, to reproduction and losses through faeces (Kooijman 2009). Individuals may grow, reproduce or die depending on the net effect of the individual level processes. By following the environment and the fate of all individuals over time, the population level dynamics are an emergent property of such models. The EBT model allows for the modelling of a dynamic resource, so that individual energy uptake lead to (local) resource depletion and potentially induce resource competition.

An agent-based model was used to model the fishing fleet. In this model, individual vessels follow a harvesting strategy based on catch results and movement costs, as described in detail below. To our knowledge, this is the first time such a combination of highly mechanistic ecological and fleet behaviour models has been used.

The model describes the shrimp population and fleet dynamics in the eastern coastal zone of the North Sea from the south of the Netherlands up to the Danish west coast (Figure 5). The zone is divided into nine areas, based on the spatial distribution of the shrimp fleet, estimated from VMS data (Ch. 3). Each area contains a relatively shallow and a relatively deep region, based on the assumption that small and large shrimp are separated in space and do not compete with each other for resources, nor are small shrimp prone to fishing mortality in their shallow habitat (Janssen and Kuipers 1980). It is assumed that shrimp move from the shallow to the deeper region when they reach a length of 2.5cm.

Table 5. Variables, equations and functions for the shrimp population, physiology and the resources. Index *i* denotes an individual shrimp cohort and index *j* denotes an area.

Variables		
Number of cohorts	D	
Number of individuals in cohort *i*	$N_i, i \in \{1, D\}$	
Volume of individuals in cohort *i*	V_i	
Energy of individuals in cohort *i*	E_i	
Reproductive energy of individuals in cohort *i*	$E_{r,i}$	
Resource density in area *j*	R_j	
Brown shrimp dynamics		
Volume of individuals in cohort *i*	$\frac{dV_i}{dt} = \kappa P_E - M/[E_G]$	1
Energy of individuals in cohort *i*	$\frac{dE_i}{dt} = \varepsilon I - P_E$	2
Reproductive energy of individuals in cohort *i*	$\frac{dE_{r,i}}{dt} = (1-\kappa)P_E - P_R$	3
Number of individuals in cohort *i*	$\frac{dN_i}{dt} = -(\mu + \mu_s + \mu_f)N_i$	4
Resource dynamics		
Resource density in area *j*	$\frac{dR_j}{dt} = R_j\left((Rf_\tau K) - R_j\right) - R_j(\sum_{i=1}^{D} S_m S A_\tau / Area_j)$	5

Table 5. continued

Brown shrimp functions		
Maximum intake	$I_m = \{\mathrm{PXm}\}\, V_i^{2/3}$	6
Search time	$S = 1/\left(1 + R_j\, \{\mathrm{PXm}\}/I_m\right)$	7
Ingestion	$I = A_\tau\, S_m\, R_j\, S$	8
Maintenance	$M = A_\tau\, [P_M] V_i$	9
Energy utilisation	$P_E = \frac{{E_i}/{V_i}}{\kappa\, {E_i}/{V_i} + [E_G]} \cdot \left(\frac{\left(\{\mathrm{PXm}\}\, {E_i}/{V_i}\, \varepsilon\, V_i^{\frac{2}{3}}\right)}{[E_M]}\right) + M$	10
Development and maintenance of maturity	$P_R = \begin{cases} \frac{V_i\,(1-\kappa)}{\kappa} M \; if\; V_i \leq V_P \\ \frac{V_P\,(1-\kappa)}{\kappa} M \; if\; V_i > V_P \end{cases}$	11
Cohort addition	$C \rightarrow C + 1$	12
Larvae numbers	$N_i = \sum_{i=1}^{D-1} E_{r,i}\, N_i$ for $V_i > V_p$	13
Background mortality	$\mu = \mu_b + C_\mu\, V_i^{-E_\mu}$	14
Starvation mortality	$\mu_s = \begin{cases} 0 \; if\; \frac{V_i}{V_{max}} \geq S_t \\ S_r\left(\frac{S_t}{(V_i/V_{max})} - 1\right) if\; \frac{V_i}{V_{max}} < S_t \end{cases}$	15
Length	$L_i = V_i^{1/3}/\delta_m$	16
Net selectivity (the fraction of individuals in cohort *i* of length L_i which dies in a single trawl pass)	$N(L_i) = \frac{1}{\left(1 + e^{\left(L50\frac{1}{L50-L25} - L_i\frac{1}{L50-L25}\right)}\right)}$	17
Effort in area *j*	$D_j = \sum_i fishing\ days$	18
Fishing mortality	$\mu_f = -\ln(1 - N(L_i))\, \frac{\frac{D_j}{7} F_s}{Area_j}$	19
Ambient temperature in area *j*	$T_\tau = amp_j \sin\left(\pi \frac{(\tau - center_j)}{width_j}\right) + offset_j$	20
Arrhenius scaling at day τ	$A_\tau = e^{\frac{TA}{Tref} - \frac{TA}{T_\tau}} \cdot \frac{\left(1 + e^{\frac{TAL}{Tref} - \frac{TAL}{TL}} + e^{-\frac{TAH}{TH} - \frac{TAH}{Tref}}\right)}{\left(1 + e^{\frac{TAL}{T_\tau} - \frac{TAL}{TL}} + e^{\frac{TAH}{TH} - \frac{TAH}{T_\tau}}\right)}$	21
Resource functions		
Resource productivity seasonal scaling	$Rf_\tau = amp \sin\left(\pi \frac{(\tau - center)}{width}\right) + offset$	22

4.1.2.1 Brown shrimp physiology

The functions describing individual shrimp intake, growth and energy allocation to reproduction are taken from (Campos et al. 2009). All are a function of the body volume of an individual (van der Meer 2006)(Table 5) and we assume that all individuals in a cohort are identical (DeRoos et al. 1992). Intake and maintenance are temperature dependent following (Campos et al. 2009) (Table 5, eq. 6-9), with area specific temperature curves based on hydrodynamic modelling of the bottom layer of the coastal zone of the North Sea along the area of interest (Delft3D model, DELTARES, *unpublished data*). Comparison of an experimentally determined handling time (Andresen and van der Meer 2010) and maximum ingestion rate based on gut capacity (Campos et al. 2009) indicates that gut capacity is a stronger limiting factor in the acquisition of food. Hence, we assume that digestion limits resource consumption (Table 5, eq. 8). Based on a 12 hour activity span and the data presented in (Andresen and van der Meer 2010) a search rate of $1.5 m^2 d^{-1}$ was determined. Food consumption is modelled as a saturating function using the maximum intake rate scaled with food encounter rate (Table 5, eq. 8).

Other shrimp parameters were taken from (Campos et al. 2009) (Table 6). The net energy intake is a function of intake and maintenance, of which a fraction κ is invested in volumetric growth (van der Meer 2006, Kooijman 2009)(Table 5, eq. 1-2). The remaining fraction of assimilated energy (1-κ) is used for reproduction (van der Meer 2006) (Table 5, eq. 3). All individuals invest energy into maturation, i.e. into the development as well as maintenance of the reproductive organs (Table 5, eq. 3) (Kooijman 2009).

Reproduction occurs twice per year, in early June and in mid-November, coinciding with a peak in egg presence found in brown shrimp along the German coast (Temming and Damm 2002). The number of larvae produced is determined by summing the reproductive energy from all adult individuals in all cohorts, and dividing by the energetic content of an egg plus the energetic cost of creating the corresponding volume (Table 5, eq. 13). The reproductive energy of all contributing individuals is subsequently reset to 0. The total number of larvae are redistributed proportional to the size of each area, so that each area receives an identical density (numbers per unit surface area) of larvae. We assume larvae to be born at a length of ~0.15mm, and to feed on pelagic resources (which are assumed to be highly available) until they reach 0.5cm, at which length they settle on the sea floor in the shallow regions and begin feeding on the benthic resource. Larvae do suffer from background mortality during both the pelagic and the benthic phase. This background mortality has a size-dependent component which exponentially decreases with increasing body size, and a baseline mortality for all sizes, which is based on estimates of natural mortality for large shrimp (Table 5, eq. 14) (Temming and Hufnagl 2015).Upon reaching volume V_M, corresponding to a length of ~2.5cm, individuals move from the shallow to the deep habitat, as larger shrimp are found in deeper waters (Janssen and Kuipers 1980). In the deep habitat, fishing mortality occurs, with a length-based net-selectivity (Polet 2000) (see below).

When food is scarce, shrimp individuals can compensate by ‘shrinking’ in volume. However, when a threshold value for body condition (the ratio individual volume to maximum volume) is reached, starvation mortality occurs. The experienced starvation mortality is proportional to the volume deficit (Table 5, eq. 15).

4.1.2.2 Resources

Each shallow and deep area has its own resource, which follows semi-chemostat dynamics in absence of shrimp foraging (Table 5, eq. 5). Maximum resource density is the same between areas and follows a sine function with an average level of 3000 kJ/m^2, based on Wadden Sea benthos density (Beukema et al. 1978) and caloric content of species and/or species groups (Brey et al. 1988) (Table 5, eq. 22). DEB model parameters are based on caloric values, and hence we have chosen to model the resource as a ‘caloric density’. The caloric food density of each area feeds into the individual level shrimp model for the individuals present in that particular area. The total consumption rate, summed over all individuals present in the area is then subtracted in the resource equation (Table 5, eq. 5).

4.1.2.3 Fishing

Fishing mortality occurs only in the deep regions and hence only targets shrimp larger than 2.5cm. The actual fishing mortality is a function of the combined activity of all vessels present in the area (Table 5, eq. 16-19). Based on a combination of data analysis (VMS) and consultation of representatives of the shrimp fishery (Chapter 3), the fleet has been divided into ‘local’ and ‘global’ vessels. The first (and largest) group are fishermen which are predominantly active on a single area. Their choices are limited: fishing, or stay in harbour. Each fished area has a fleet of 40 local vessels. The second group is more widely mobile and may fish in any of the deep areas. These mobile vessels have the opportunity to move to a different area at the start of each week. The probability to move is based on a balance between the LPUE realized last week in each area and the cost (in terms of lost fishing time) of steaming from the current location to a new area. The higher the landings per unit effort in an area during the previous week, the higher the probability that mobile vessels will move there in the coming week.

Each vessel is assumed to start fishing on Monday, but has an opportunity to stop fishing for the remainder of the week. The decision to give up is based on a threshold LPUE value from the initial activity. This threshold represents an absolute minimum catch of marketable shrimp, below which further fishing is deemed pointless. This ‘giving up LPUE’ differs between the local and the global movement groups, where the local fishermen are assumed to give up more easily (have higher threshold value). Furthermore, of the entire local and mobile fleet, half of the vessels do not fish for shrimp between December and February (ICES 2015), reflecting a combination of the availability of more profitable activities (fishing for sole or Norway lobster), and the prevalence of bad weather in these months, preventing smaller vessels from fishing.

We have implemented a harvest control rule (HCR), based on thresholds of the overall landings per unit effort below which allowed fishing time will be reduced. The evaluation is on a per-week basis, so that the evaluated LPUE from week x is used to determine the fishing time allowed in week x+1. A HCR with two thresholds is used: a relatively high LPUE threshold for which maximum fishing time is reduced from five to three days, and a low LPUE threshold for which the fishing time is reduced to one day. Both thresholds depend on a chosen HCR trigger LPUE. If LPUE falls below 75% of this reference value, maximum effort is decreased to three days per week, if LPUE falls below 50% of the reference value, maximum effort is decreased to one day per week. This system corresponds to that used in (Temming et al. 2013)

We assume that each 24-hour period at sea consists on average of 12 hours of fishing, at 3 knots, with two 9m-wide trawls. Hence, one fishing day equals ~120ha of fished surface.

Per area the sum of vessel effort is calculated. The imposed fishing mortality for a shrimp in a certain area is then a result of the summed effort and the net selectivity based on shrimp size. Net selectivity (N_f) was studied based on the Dutch beam trawler fleet (Polet 2000) and is described by a logistic function scaling selectivity between zero and one based on individual shrimp length (Table 5, eq. 16-17). The number of vessels is kept constant in this study at 500, with 360 locally operating vessels (40 in each of 9 areas) and 140 globally operating vessels (ICES 2013).

Table 6. All parameters and their values.

Parameter	**Symbol**	**Value**	**Unit**	**Reference**
Individuals				
Maximum search rate	M_s	1.5	$m^{-2}\ d^{-1}$	(Andresen and van der Meer 2010)
Handling	H	1		
Maximum ingestion	$\{P_{Xm}\}$	58.9	$J\ cm^{-2}\ d^{-1}$	(Campos et al. 2009)
Volume specific Maintenance	$[P_M]$	15.9	$J\ cm^{-3}\ d^{-1}$	(Campos et al. 2009)
Cost of growth	$[E_G]$	2000	$J\ cm^{-3}$	(Campos et al. 2009)
Maximum energy density	$[E_M]$	851	$J\ cm^{-3}$	(Campos et al. 2009)
Volume larva	V_L	0.0000416	cm^3	(Urzua et al. 2012)
Volume movement	V_M	0.15	cm^3	
Volume maturation	V_P	0.261	cm^3	(Campos et al. 2009)
Shape coefficient	δ_m	0.213	-	(Campos et al. 2009)
Kappa	κ	0.8	-	(Campos et al. 2009)
Conversion efficiency	ε	0.8	-	(Campos et al. 2009)

Table 7. continued

Parameter	**Symbol**	**Value**	**Unit**	**Reference**
Starvation mortality rate	S_r	0.5	d^{-1}	
Starvation threshold	S_t	0.75		
Background mortality rate	μ_b	0.005	d^{-1}	(Temming and Hufnagl 2015)
Size-dependent mortality constant	Cμ	0.003	d^{-1}	
Size-dependent mortality exponent	Eμ	0.35	d^{-1}	
Arrhenius temperature	T_A	9000	K	(Campos et al. 2009)
Optimum temperature	T_{opt}	296	K	(Campos et al. 2009)
Lower boundary of tolerance range	T_L	273	K	(Campos et al. 2009)
Upper boundary of tolerance range	T_H	303	K	(Campos et al. 2009)
Rate of decrease at lower boundary	T_{AL}	6,700,000	K	(Campos et al. 2009)
Rate of decrease at upper boundary	T_{AH}	49,368	K	(Campos et al. 2009)
Resource				
Carrying capacity	K	3000	J/m^2	
Regrowth rate	r	0.045	d^{-1}	
Fishing				
L25 net selectivity	L_{25}	3.4	cm	(Polet 2000)
L50 net selectivity	L_{50}	3.94	cm	(Polet 2000)
Commercial size	L_c	5.0	cm	(ICES 2015)
Day surface	F_s	1,260E3	m^2	(Polet 2000)
Fleet size	NV	500		(ICES 2015)
Giving up threshold local vessels		50	kg	
Giving up threshold global vessels		25	kg	
HCR threshold high		0.75	-	
HCR threshold low		0.5	-	
HCR fishing time low		1	d/w	
HCR fishing time high		3	d/w	
Maximum fishing time		5	d/w	

5 Model results

5.1 Results in the current situation

5.1.1 Brown shrimp population

Each year, two cohorts are added to the population as reproduction peaks. A summer cohort is produced in mid-June, and a winter cohort in late November (Figure 6 and Figure 7). Individuals in these cohorts are born as very small larvae (~1.4mm) and grow at maximum rate until they reach 5mm. At that size, they settle in the shallow benthic habitat and start feeding on the shallow resources. As a result, these resources strongly decline, particularly after settlement of the (larger) summer cohort. The summer cohort is larger initially, but also grows more slowly than the winter cohort (Figure 7). As a result, it is exposed to background mortality for a longer period of time than the winter cohort, and by the time it reaches commercial size, consists of fewer individuals than the winter cohort.

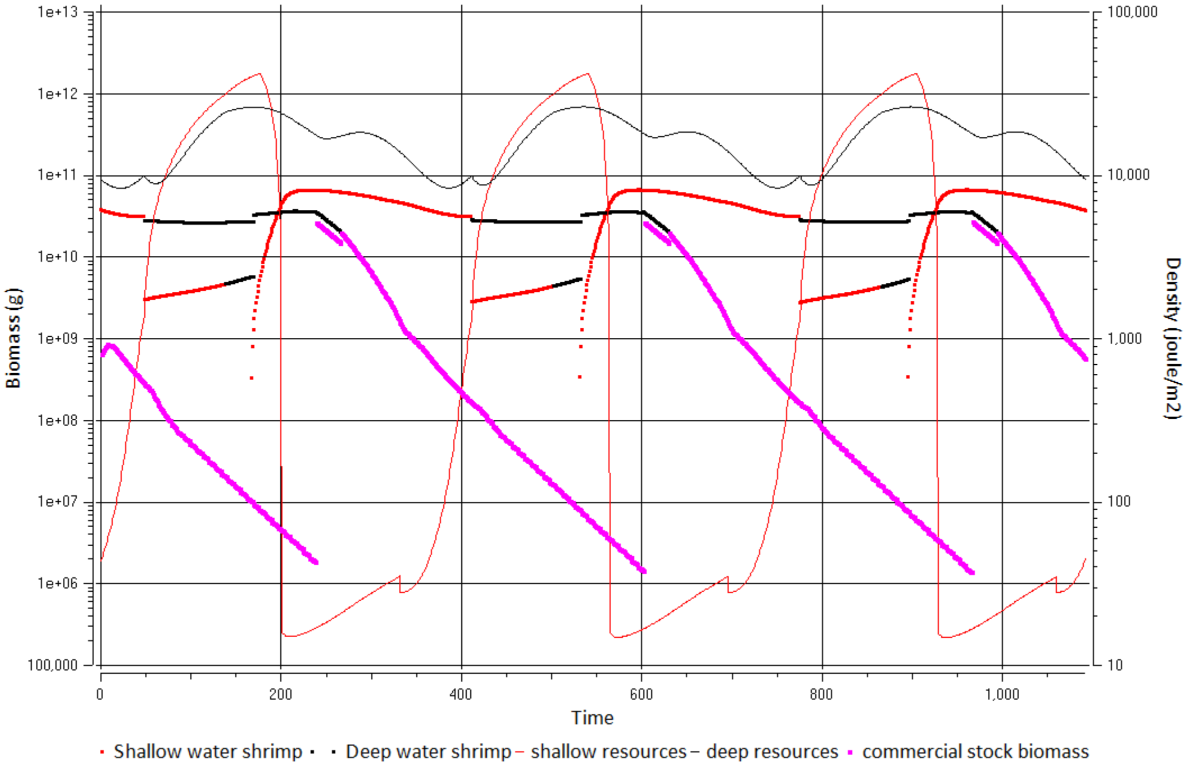


Figure 6: Dynamics of the shrimp population biomass and its food (resources) over a period of 3 years (1092 days), starting on the 1st of January. Each year, two cohorts are added to the population. One in December (winter cohort) and one in June (summer cohort).

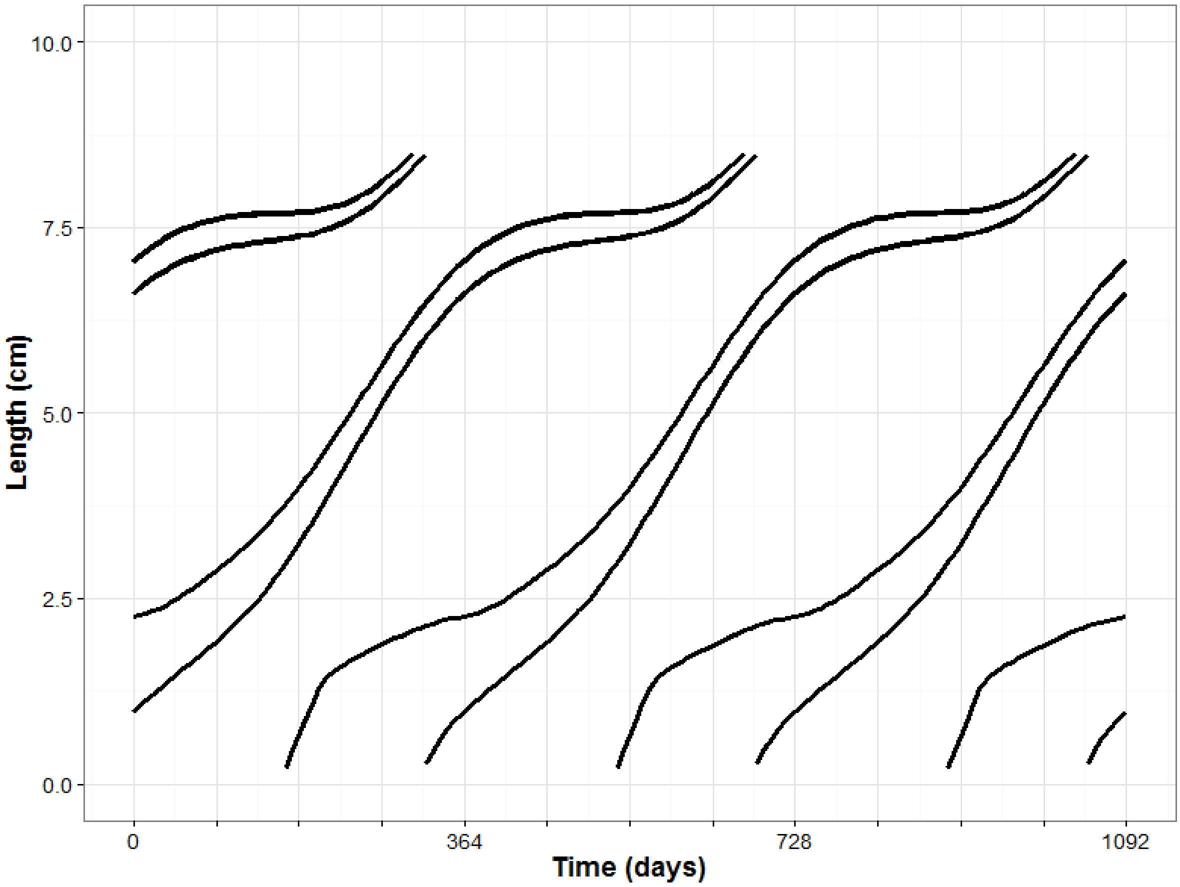


Figure 7: Growth curves of the summer and winter cohort. Time 0 is the 1st of January, 1092 the end of a 3-year period. The summer cohort (born in June) has a period of relatively slow growth from around 1.5 to 2.5 cm. This delayed growth, which is caused by a combination of intra-cohort competition and the onset of winter, results in size convergence with the next winter cohort. Winter cohorts grow faster, as the temperatures strongly increase shortly after they settle in the benthic habitat.

5.1.2 Fleet dynamics

In the standard model setting, representing the ‘current situation’, total annual catches of brown shrimp are ~45000 tons, of which ~30000 tons are landings (marketable shrimp, >5cm). Associated discards of undersized shrimp are ~15000 tons annually, meaning that approximately 1/3rd of total annual catches consist of discarded undersized shrimp. The distribution of fishing vessels over the areas shows a clear pattern during the year (Figure 8). Sylt, the Danish west coast and the German Wadden area show peaks in attendance of fishermen in June and December, at which time the other areas are relatively empty. In March and September-October, fishing vessels are spread relatively evenly over all areas.

The pattern in effort for each area reveals a general annual pattern of highest effort in September to November. Some activity continues over winter for those vessels that do not stop for the winter, while March-September is a period of very low activity (Figure 9). The pattern in effort is matched by that in catches, which peak in week 36 (early September) when the most recent winter cohort reaches commercial size, and then gradually decline over time (Figure 10), which is also clearly reflected in the change in LPUE by week (Figure 11). Discard rates are high throughout spring and summer, but are zero in autumn and winter (Figure 12). The absence of discards between week 40 and week 7 of the following year is a result of that the model contains much less random variation than the real system. The prediction taken from this for the North Sea shrimp fishery should be that discards are substantially lower in the fourth and first quarter of each year. See section 6.1 for more discussion on the relationship between model output and the real system.

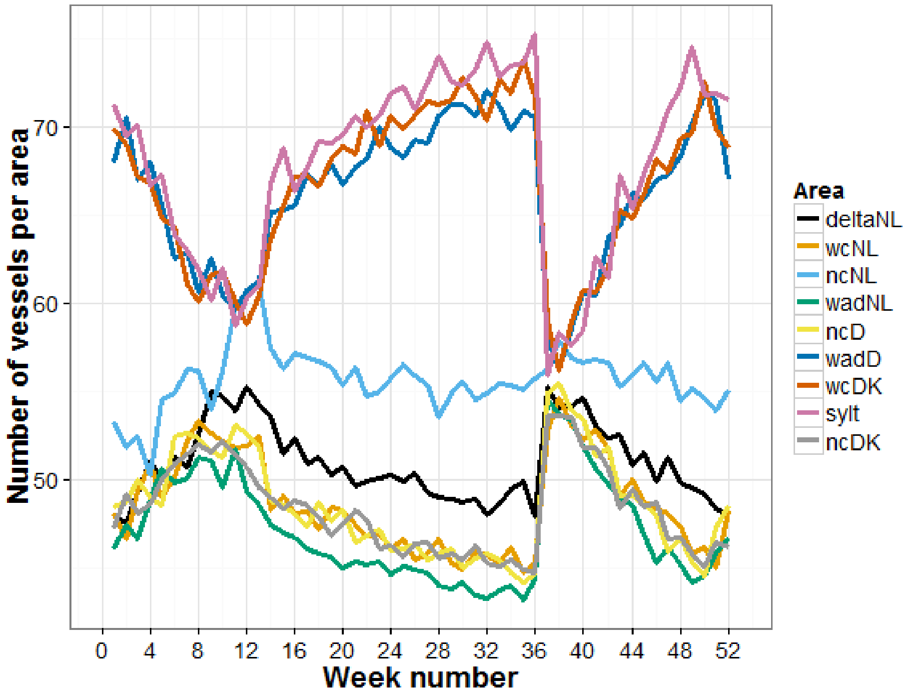


Figure 8: Average distribution of fishing vessels targeting brown shrimp over areas for each week in the year. Note that all vessels are included in this plot, even those that are not fishing.

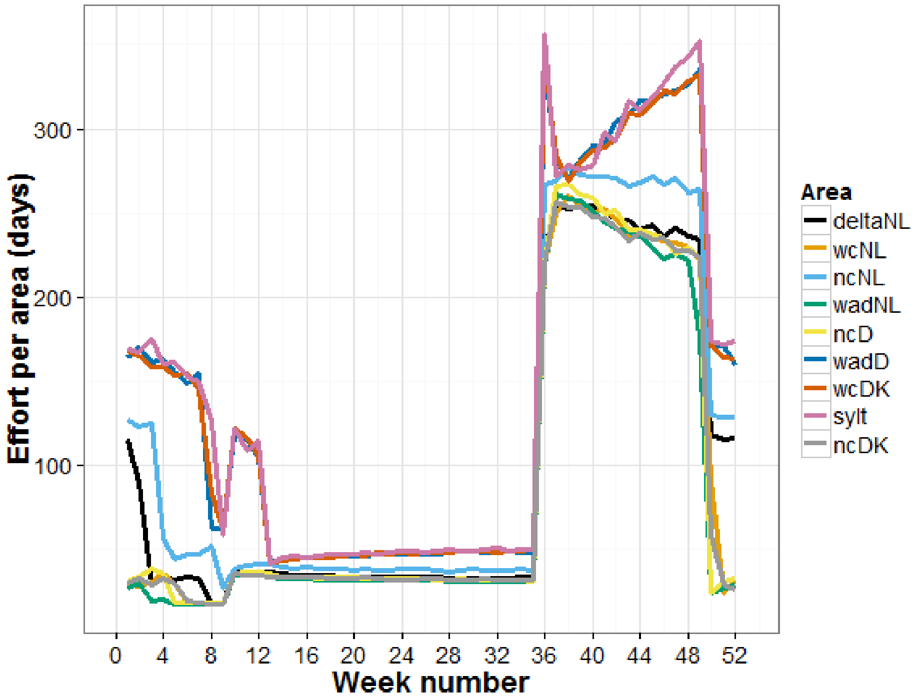


Figure 9: Total effort of the fleet targetting brown shrimp per modeled area (days/week). The period from week 14 to week 35 is characterized by ‘trial fishing’: catches are so low that vessels decide after a brief fishing trip to give up, and try again next week. Eventually, in week 36, this year’s winter cohort and last year’s summer cohort reach commercial size (5cm) and effort spikes.

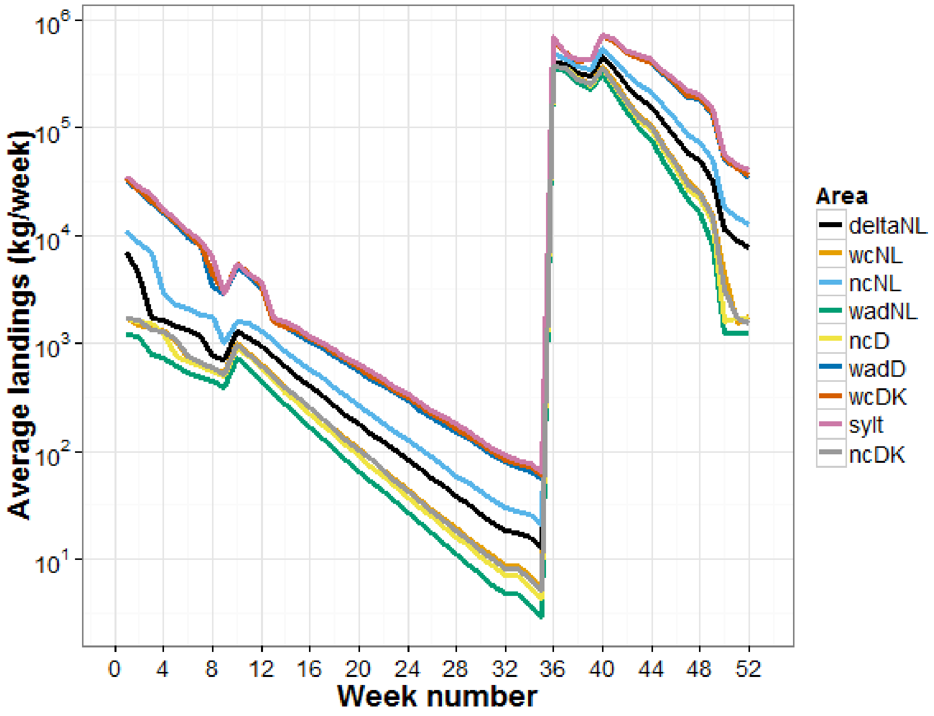


Figure 10: Average landings of brown shrimp per week for each area (totals for all vessels active in each area). The pattern is dominated by the large spike in catches in week 36, as the most recent winter and summer cohort reach commercial size, and the decline in catches as these cohorts are depleted as a result of fishing and other mortality.

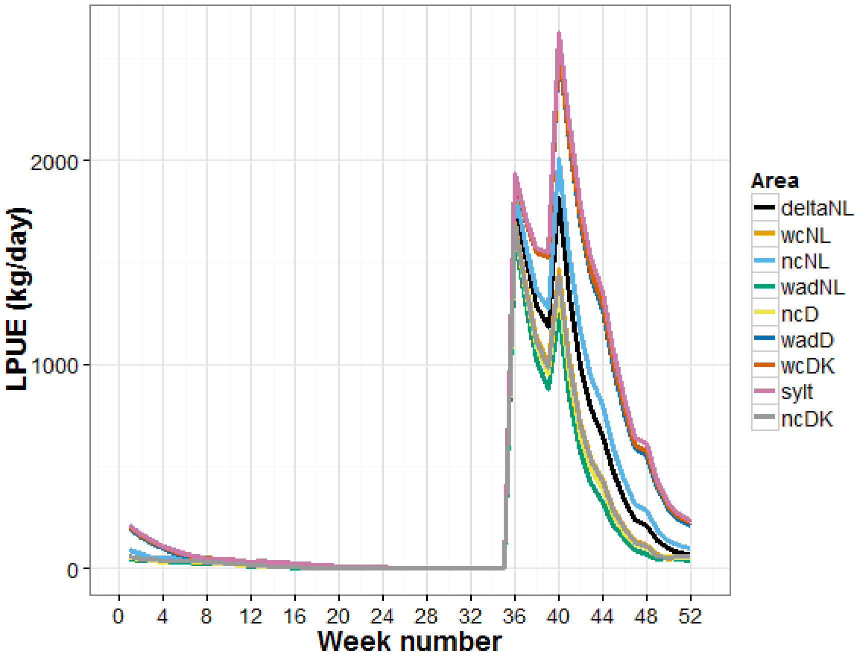


Figure 11: Average landings of brown shrimp per unit effort (LPUE) by week for each area. The pattern is dominated by the large spike in catches in week 36, as the most recent winter and summer cohort reach commercial size, and the sharp decline in catches as these cohorts are depleted as a result of fishing and other mortality.

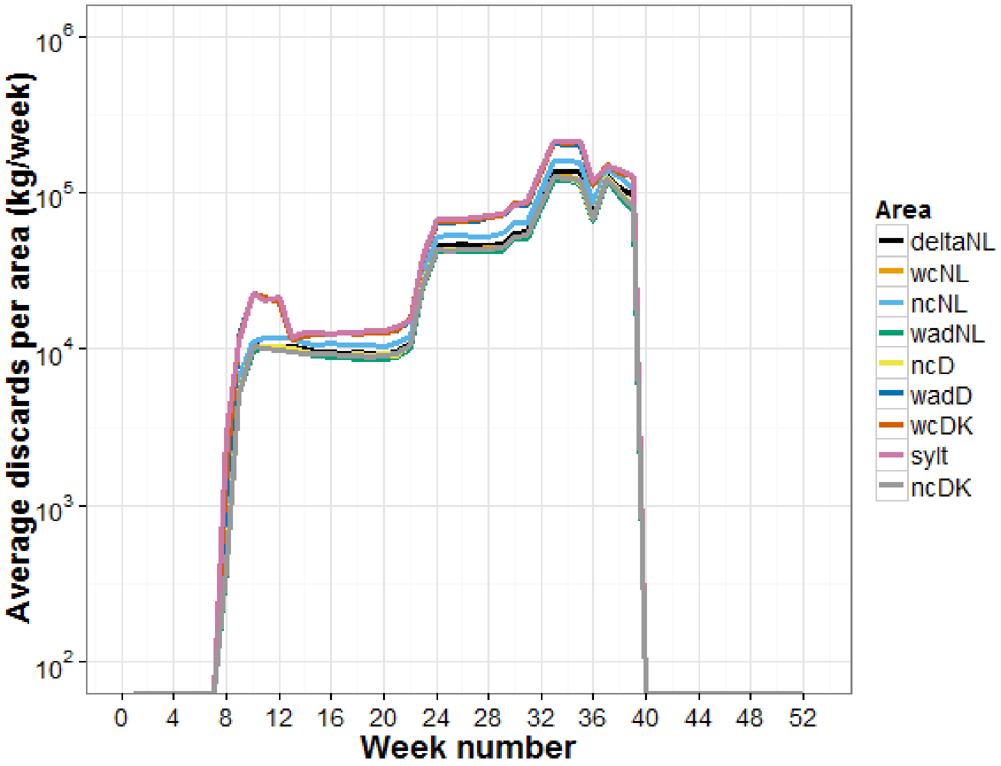


Figure 12: Average discards of brown shrimp (< 50mm) per week for each area (totals for all vessels active in each area). The pattern is dominated by a disappearance of bycatch in week 40, as all shrimp present in the population reach commercial size. The absence of discards between week 40 and week 7 of the following year is a result of that the model contains much less random variation than the real system. The prediction taken from this for the North Sea shrimp fishery should be that discards are substantially lower in the fourth and first quarter of each year. See section 6.1 for more discussion on the relationship between model output and the real system.

5.1.3 Comparing model fleet behaviour with observational data

The patterns found in the model output can be related to those observed in the data. Comparing the effort data for vessels operating globally with similar vessels extracted from the VMS database (Figure 13) shows that the clear dip in effort in spring and early summer which is observed in the model output, also appears to be present in the data. For the vessels operating in the Dutch Wadden Sea, the pattern is less obvious in the data. This may be due to a higher willingness for this fleet to go out even when catches are low. The LPUE for the Dutch Wadden Sea vessels (Figure 14) does show a peak in the second half of the year, corroborating this hypothesis. This same pattern is also found in the LPUE data for the globally operating vessels.

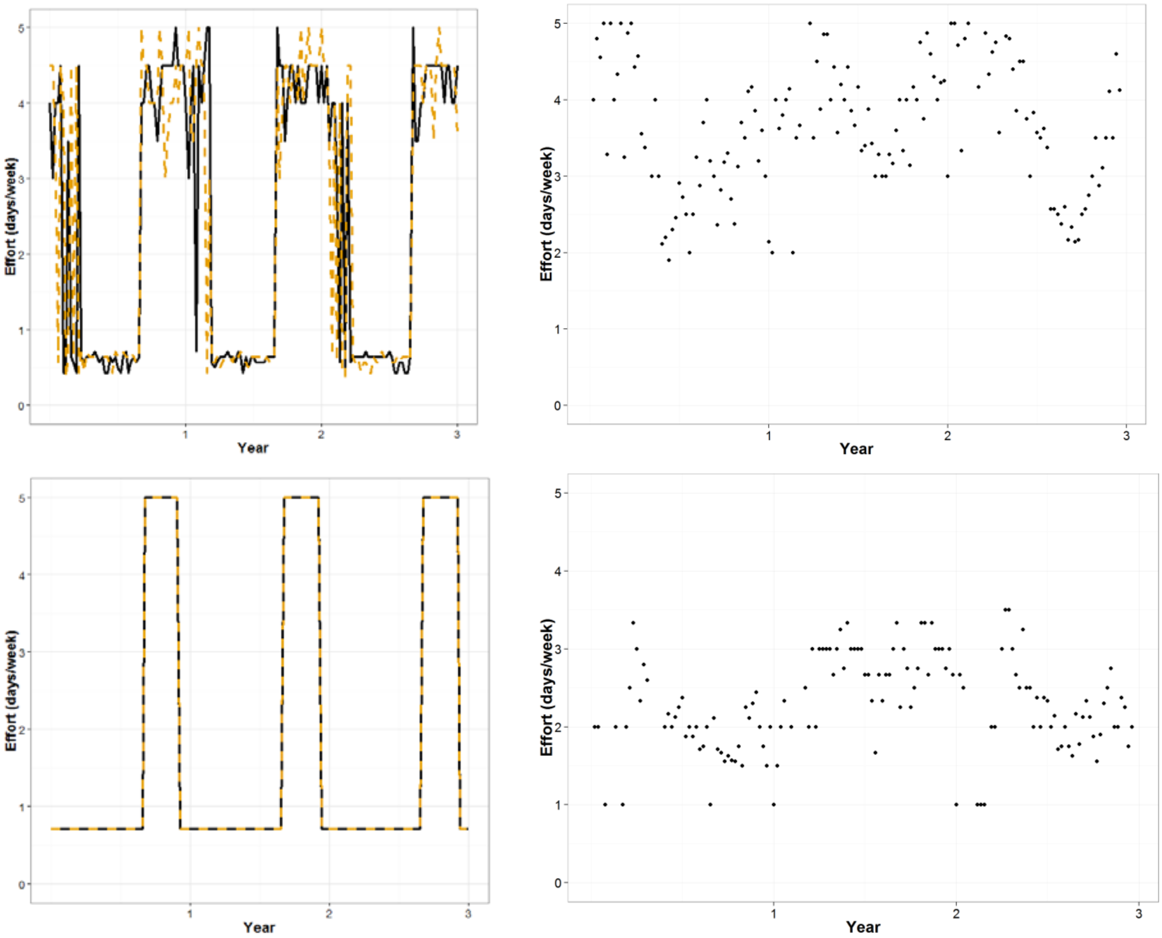


Figure 13: Effort (days/week) by a random sample of two ‘globally operating’ vessels in the model (top left) and for the most mobile vessels in the Dutch fleet (top right). Bottom row shows comparable plots, but for vessels operating in the Dutch Wadden Sea area. For methods regarding data selection for the right hand panels see appendix 4.

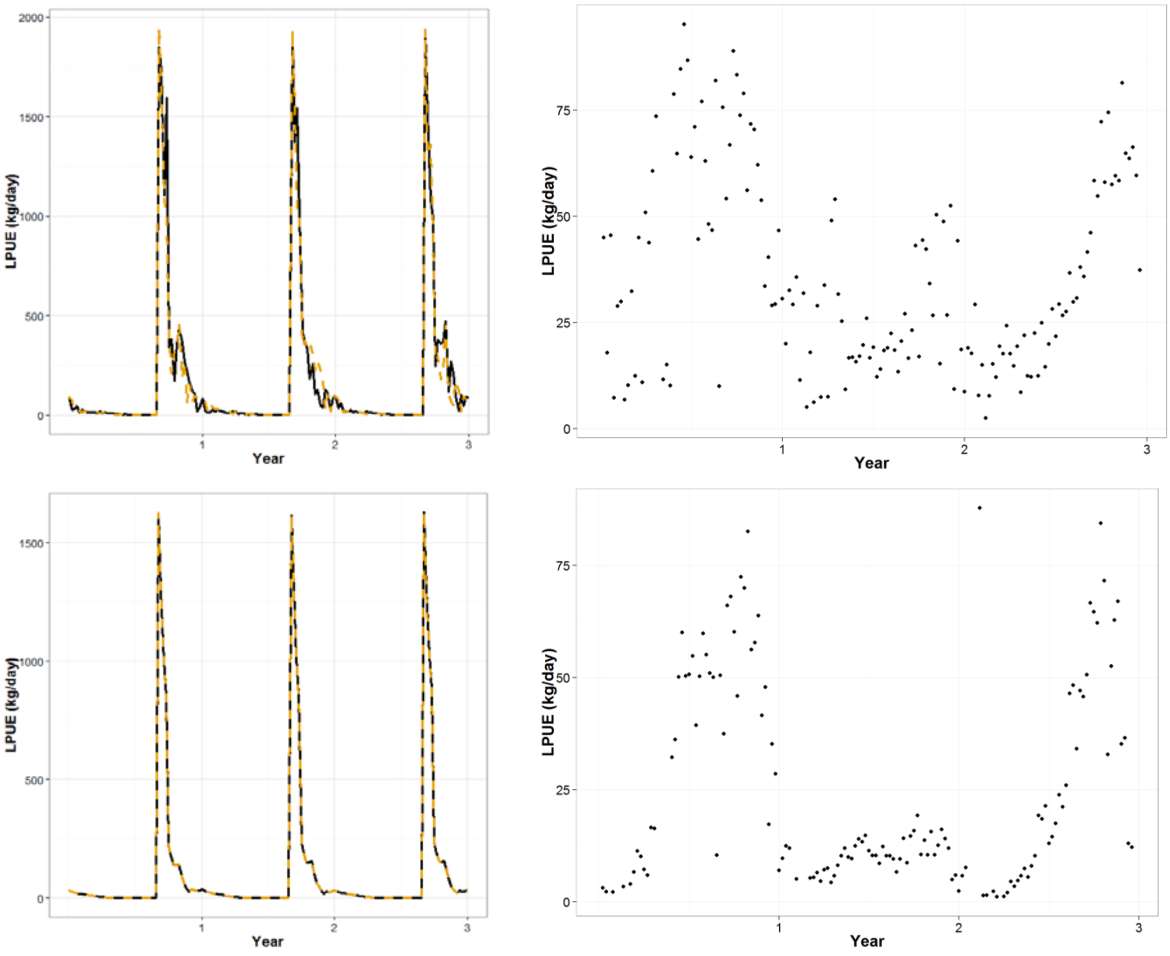


Figure 14: Catch per unit effort (kg/day) by a random sample of two ‘globally operating’ vessels in the model (top left) and for the most mobile vessels in the Dutch fleet (top right). Bottom row shows comparable plots, but for vessels operating in the Dutch Wadden Sea area. For methods regarding data selection for the right hand panels see appendix 4.

5.2 Possible management scenarios (MSC, interviews)

5.2.1 Harvest Control Rule (HCR)

The harvest control rule scenario relies on a LPUE trigger value. When LPUE falls below 75% of this trigger value, Maximum total weekly time at sea is reduced to 72 hours. When LPUE falls below 50% of the trigger value, time at sea is reduced to 24 hours (Figure 15). This HCR criterion is evaluated on a weekly basis: LPUE is evaluated at the end of each week, and if it is below 75% or 50% of the trigger value, effort for the coming week is limited.

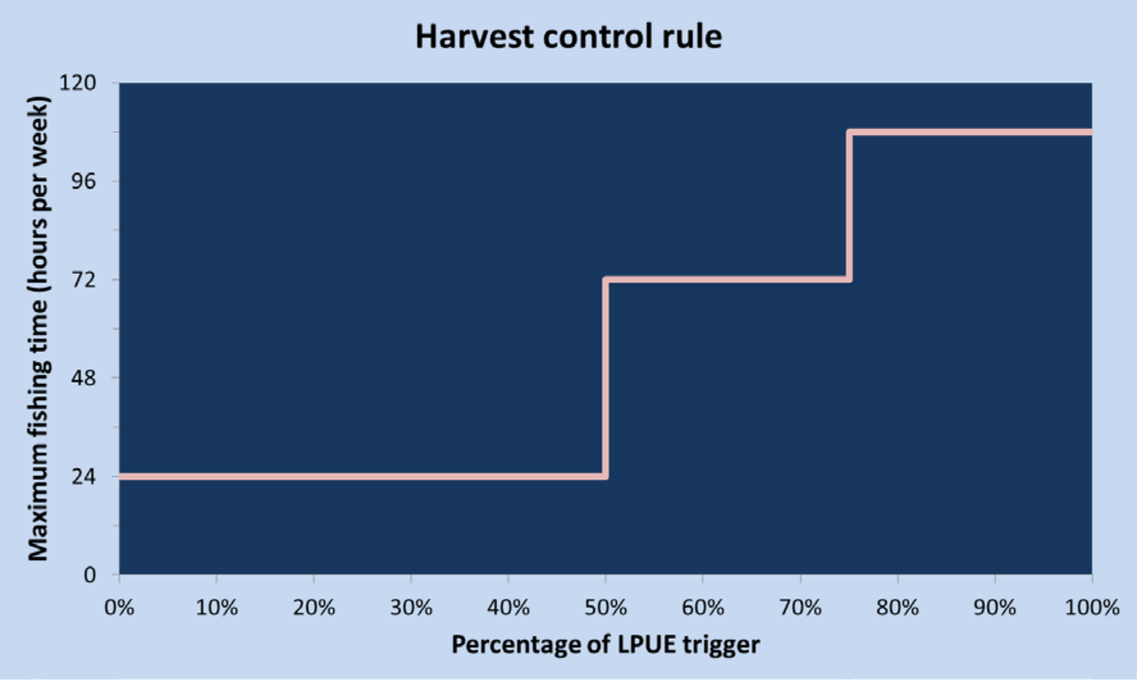


Figure 15: schematic picture of the Harvest Control Rule

5.2.2 Number of days at sea

The scenario of varying days at sea studies the effect of two alternative, but constant, maximum weekly effort limits: the entire fleet is allowed to fish only 3 days out of every week, or alternatively 7 days per week. The 3-day scenario can be seen as a 'brute force' alternative to a harvest control rule. In essence, it is a harvest control rule which always triggers. The 7 days scenario represents the idea of letting go of management entirely.

5.2.3 More/fewer ships

Here we study what happens if, compared with the current situation, the number of vessels in the fleet would be in- or decreased by 200 vessels, from 500 to 700, or from 500 to 300 vessels. The remaining vessels are then allocated over the areas and between local and global vessels in the same proportions as in the current situation, resulting in 24 local vessels per area and 84 global vessels for the 300-vessel scenario and 56 local vessels per area plus 196 global vessels in the 700-vessel scenario. .

5.2.4 Effort creep (what if all ships start fishing more efficiently)

Under this scenario, we increase the effective number of fishing hours per fishing day from 12 to 18, representing an ability to fish more effectively during daylight hours.

5.3 Results per scenario

5.3.1 Harvest Control Rule (HCR)

The results from the harvest control rule scenario can be divided into 3 general areas (Figure 16). In the first area, at very low threshold LPUE (<1kg/d), the HCR is never triggered. The threshold is simply never reached: landings never get this bad. This is essentially identical to the current situation: a HCR which never triggers is the same as not having one at all. It should be noted however that although such a 'dormant' HCR appears useless, it could still protect the stock against overfishing in the event of extreme and unexpected declines. At very high threshold LPUE (>2000kg/d), the other extreme occurs: there is a HCR which in reality is 'always on', and the maximum fishing time is reduced to only a single day per week, for each and every week of the year. This is of course identical to not having a HCR but simply reducing the effort of each vessel to 1 day per week. In between these extremes, there is a range of HCR threshold values where the effect on catches is more complex. Going from a low to a higher threshold value, total annual catches initially increase, reach an optimum, and then decrease again. Total annual discards show an opposite pattern (Figure 16). The total fleet effort is gradually reduced with increasing threshold values, while LPUE constantly increases (Figure 17 and Figure 19).

One important conclusion from the HCR simulations is that the current exploitation of brown shrimp in the North Sea occurs at an intensity which clearly leads to growth overfishing. A reduction in fishing mortality leads not only to an increased efficiency (higher LPUE) but also to higher overall catches, despite a lower effort. Furthermore, because the shrimp are allowed to grow (on average) longer, fewer are fished up before reaching commercial size, resulting in reduced bycatches of undersized shrimp.

As the HCR threshold increases, and hence the HCR is ‘switched on’ more often, the fishing mortality imposed on the shrimp is reduced, they can grow larger, and catches increase. However, with increasing HCR threshold eventually the fishing mortality is reduced to such an extent that catches go down again. This is also what is predicted to occur when exploitation is reduced from a situation of growth overfishing. At the same time however, we see that discards strongly increase, leading to an increase in discard ratio from 0.2 up to 0.55 (Figure 19). This is not a result generally associated with reduced fishing mortality, which would predict either no effect or a further decline in discarding as total effort decreases. This result is caused by the ecology of the brown shrimp population. As fewer shrimp are harvested, higher numbers remain in the water, and these individuals start to compete for food. This means they grow more slowly, taking longer to reach commercial size, and hence remain vulnerable to discarding for a longer time (Figure 22). This in turn also means that fewer individuals reach commercial size. The large increase in discards and the spike (followed by a strong drop) in landings at a threshold value of ~2000 kg/d is the net effect of a complex interplay of these two mechanisms – the reduced growth through increased competition and the increased life expectancy due to reduced mortality from harvesting. The large drop in landings is the result of a cascade of events: because the shrimp get smaller, the proportion of commercial size shrimp decreases, leading to lower landings per unit effort, leading in turn to that the HCR is triggered more often, which in turn leads to a strongly reduced fleet effort, and a concurrent strong reduction in total landings.

The effect of the reduced effort as the HCR starts to be switched on is also clearly visible in the response of the brown shrimp stock (Figure 20). Both the total stock biomass and the biomass of individuals >5cm, which are of commercial significance, increase. Furthermore, the biomass fraction of individuals >5cm in the total stock also increases gradually, from ~0.17 to ~0.22 (Figure 21). This is a further indication of a release from growth overfishing: not only is the stock size growing, the size distribution is also shifting to larger sizes. Eventually, at very high HCR threshold values, there is a steep drop in fleet effort, which in turn leads to a strong increase in stock size, leading to food competition among shrimp individuals, reduced growth and hence a strong reduction in the number of individuals over 5cm.

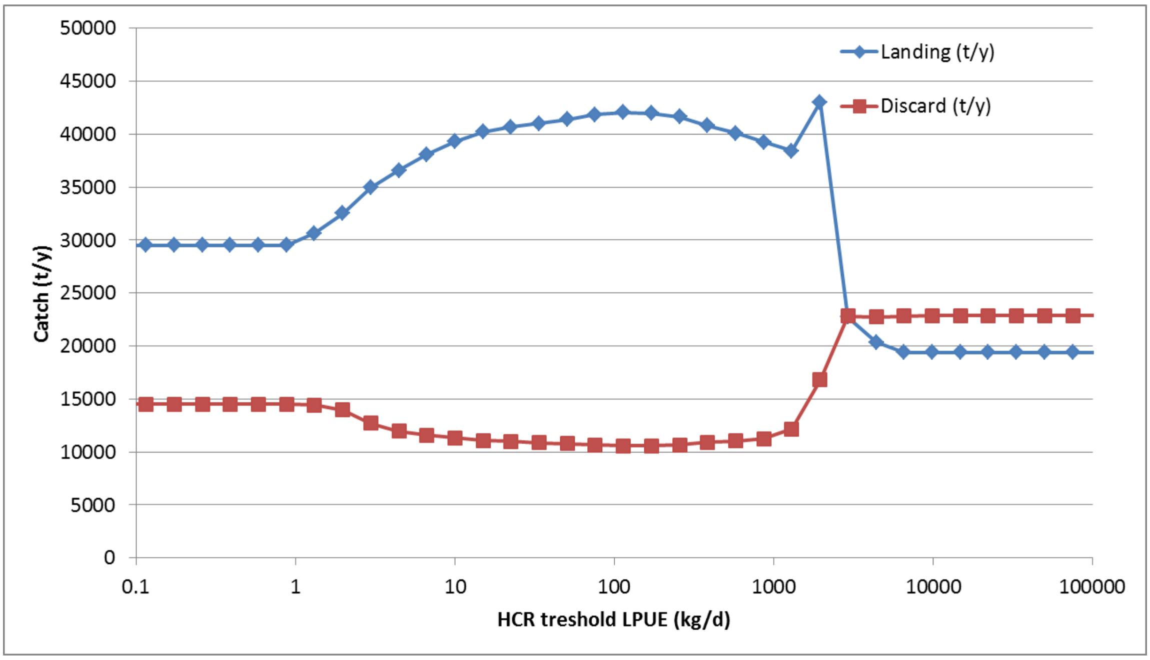


Figure 16: Changes in total annual catches and discards by the entire fleet in relation to HCR threshold LPUE.

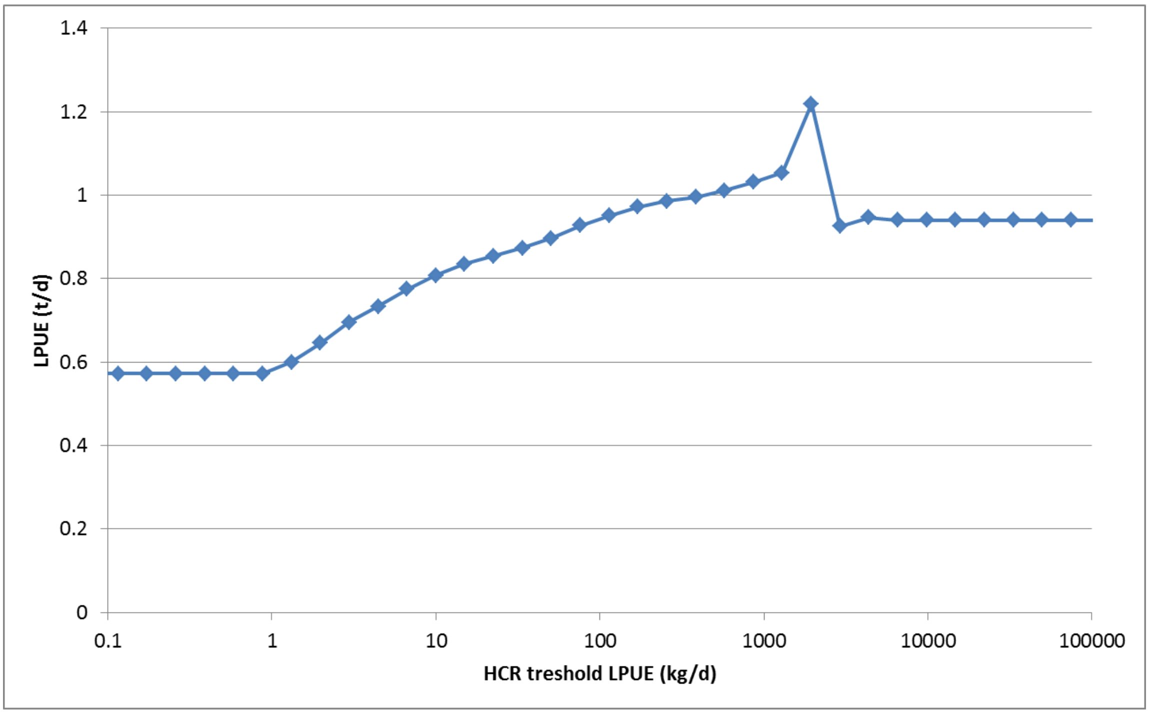


Figure 17: Average landings per unit effort in relation to HCR threshold LPUE.

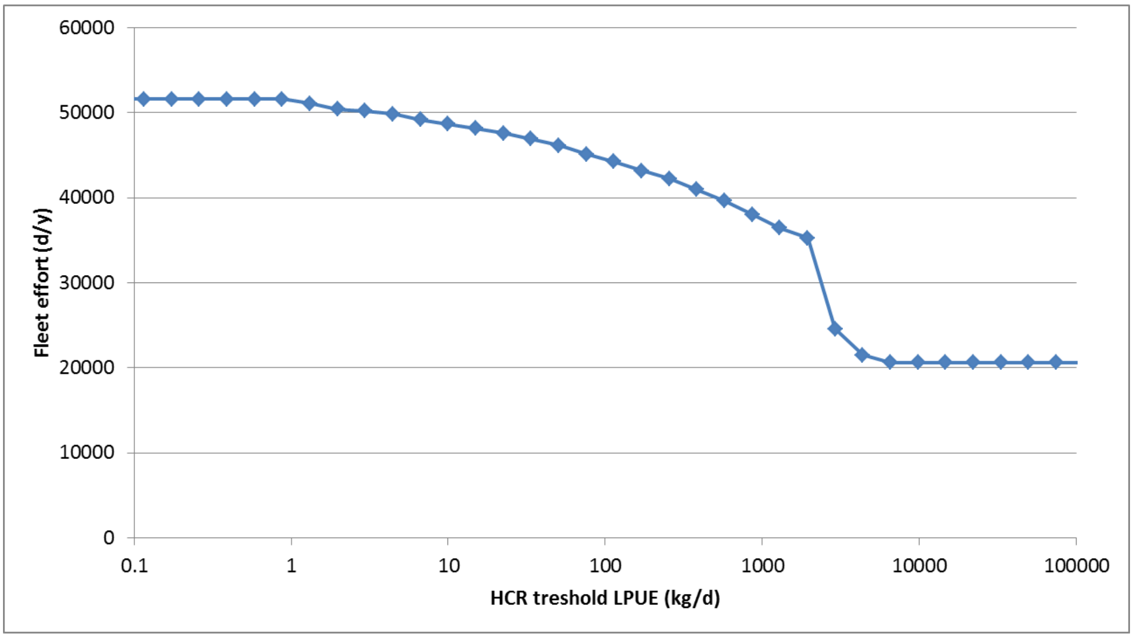


Figure 18: Average total effort (in fishing days) per year in relation to HCR threshold LPUE.

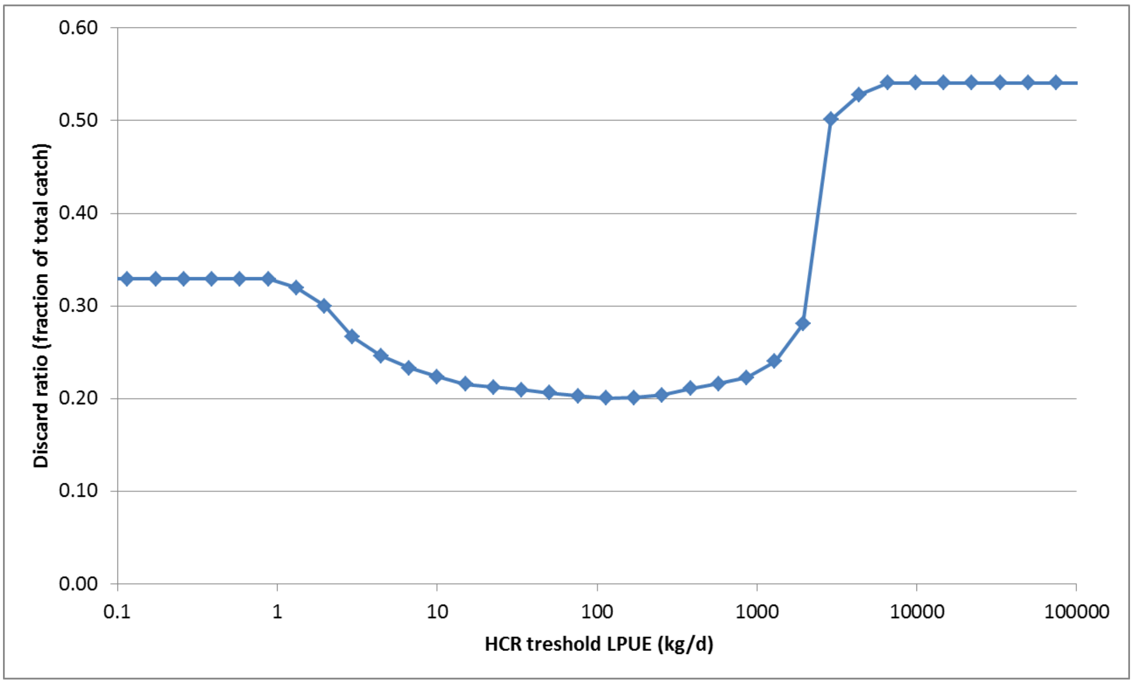


Figure 19: Average discard ratio (discards divided by the sum of discards and landings) per year in relation to HCR threshold LPUE.

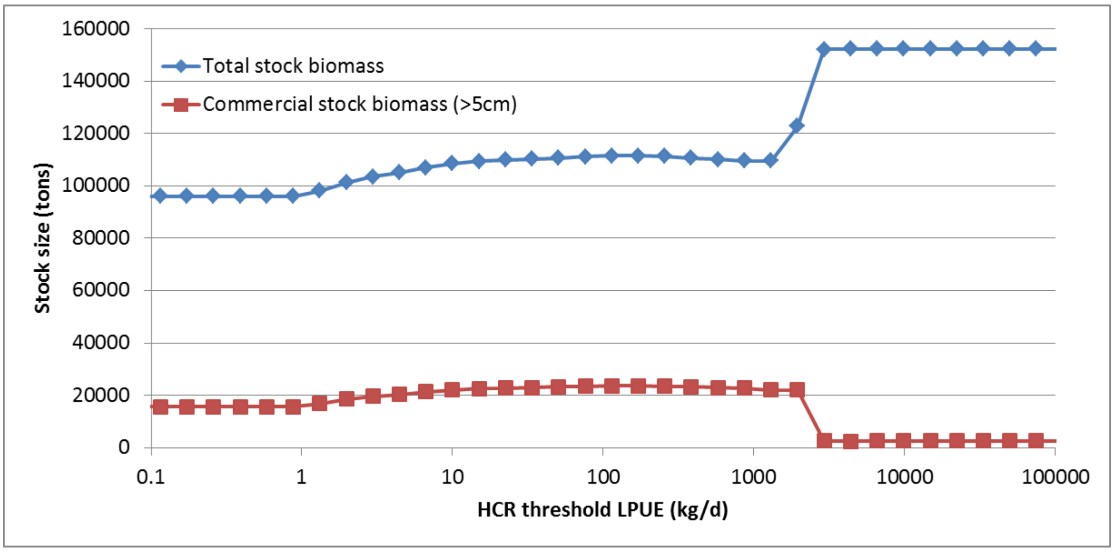


Figure 20: average biomass of the total stock and of the commercial stock (all individuals >5cm). Averages have been computed from stock size snapshots on at the start of the 3rd quarter of each year, coinciding with the timing of the DFS survey.

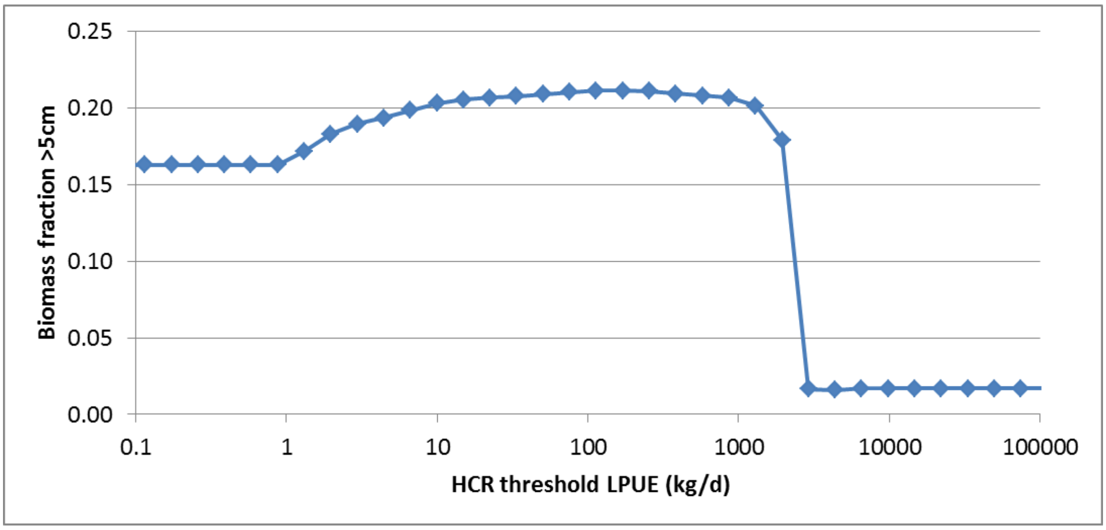
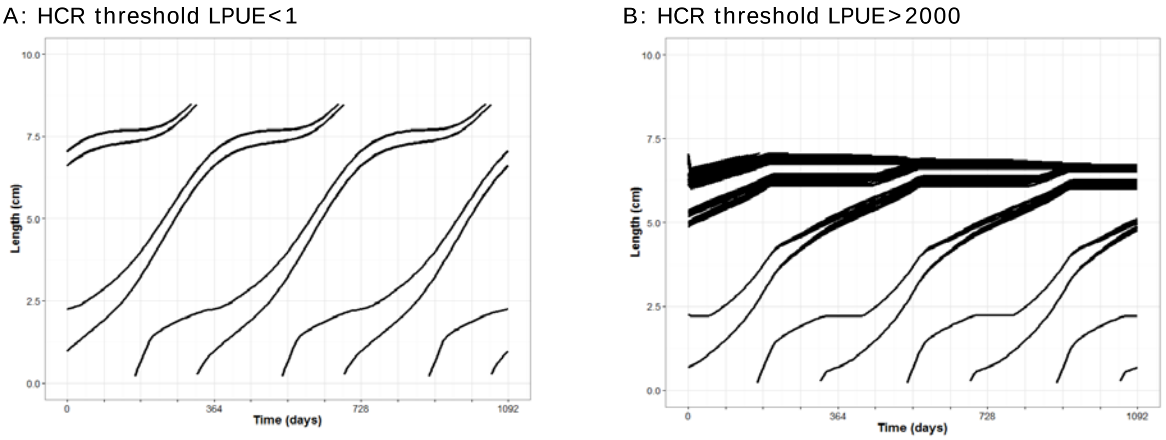


Figure 21: average fraction of the total stock biomass which is of commercial size (>5cm). Averages have been computed from stock size snapshots on at the start of the 3rd quarter of each year, coinciding with the timing of the DFS survey.


A: HCR threshold LPUE<1

B: HCR threshold LPUE>2000

Figure 22: Brown shrimp growth curves at high (A) and very low (B) exploitation rates. Time 0 is the 1st of January, 1092 the end of a 3-year period. At low exploitation rates shrimp live much longer, but also reach much lower asymptotic size (~8.5cm in A versus ~7cm in B). This explains the reduced catches. They also take much longer to grow from 2.5 to 5 cm (~4 months minimum in A versus >6 months minimum in B), which explains the increased discards.

5.3.2 Number of days at sea

The effect of limiting the fishing effort to 3 days per week is similar to introducing a HCR: it reduces growth overfishing, reduces effort from ~52000 to ~45000 days per year and increases total annual landings from ~30000 to ~35000 tons. How this occurs is most clearly seen in the annual pattern in catches (Figure 23). The peak in landings is shifted from week 36 to week 42 (compare Figure 10 and Figure 23), because the reduced exploitation rate causes a slight delay in growth rates, but the period of high catches which follows is substantially longer, allowing the surviving individuals to grow more before being harvested. Note that catches are substantially lower than the optimum possible with a harvest control rule.

Increasing maximum fishing time to 7 days leads to an increase in total effort from ~52000 to ~60000 days per year, and a total landing reduction from ~30000 to ~26000 tons annually. Note that the increase in effort is less than proportional to what is allowed: from 5 to 7 days is a 40% increase, while from 52000 to 60000 is only a 15% increase. This is because the reduced landings also lead to a higher incidence of ‘giving up’ behaviour: fishermen giving up after only a short trial run, due to very low landings. A similar effect occurs in the 3 day scenario, but in the opposite direction: the increasing landings mean less ‘giving up’.

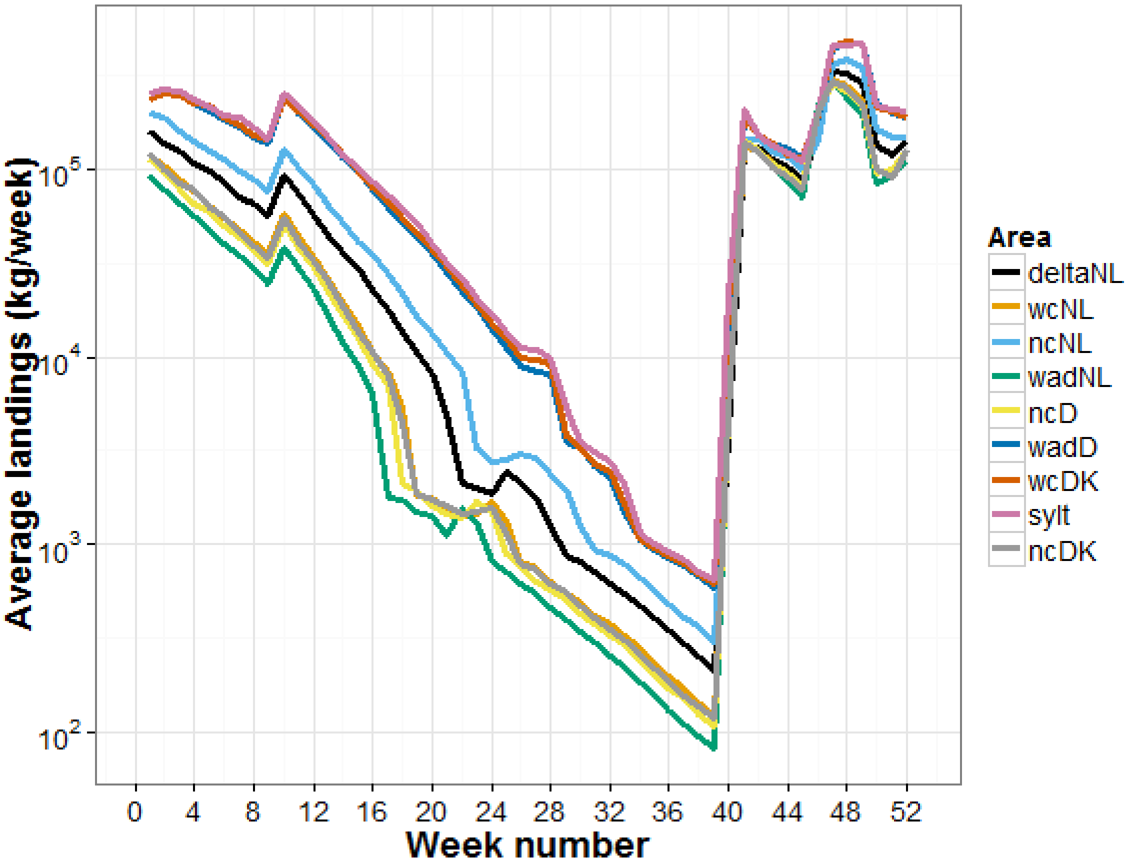


Figure 23: Average landings per week for each area (totals for all vessels active in each area) when fishing is limited to 3 days per week per vessel.

5.3.3 *More/fewer ships*

Decreasing the fleet size from 500 to 300 vessels is, on a fleet level, similar to going from a 5- to a 3-day week limit: annual effort decreases from 52000 to 46000 days, while landings increase from 30000 to 37000 tons. On the vessel level however, the reduced fleet size means that the increase in landings is shared among fewer vessels. So on a per-vessel basis, landings more than double, from ~60 to ~123 tons annually, while average annual effort per vessel increases from ~104 to ~153 days, a ~50% increase. Average LPUE on fleet level goes from 575 kg/day to 800 kg/day, further indicating the increased efficiency of the reduced fleet.

Similarly, increasing the fleet size from 500 to 700 vessels is, on a fleet level, similar to going from a 5-to a 7-day week limit: annual effort increases from 52000 to 58500 days, while landings decrease from 30000 to 26500 tons. On the vessel level the effects are amplified as these landings are realized by a larger number of vessels. Landings per vessel decrease from ~60 to ~38 tons annually, while average annual effort per vessel decreases from ~104 to ~84 days. Average LPUE goes from 575kg/day to 450kg/day, further indicating the reduced efficiency of the larger fleet.

5.3.4 *Increased efficiency*

Similar to the 7-days and 700 vessels scenario's, this scenario where effort per fishing day is increased by 50% also increases the degree of growth overfishing. Total landings decrease from ~30000 to ~24000 tons annually, while effort apparently decreases from 52000 to 40000 days. However, each day represents 1.5 times the original effort, so that these 40000 days are comparable to 60000 days of the original fleet.

6 Discussion and conclusions

6.1 Model

We have constructed and analysed a model of the dynamics of brown shrimp and its fishery. The model for brown shrimp is a dynamic energy budget (DEB) model (Kooijman 2009), the population dynamics are modelled using the physiologically structured population dynamics framework (DeRoos et al. 1992), and the fleet dynamics model uses an agent-based modelling approach (Grimm et al. 2005). Each of these approaches is highly mechanistic, meaning that it is based on the processes which lead to observed patterns, rather than on the patterns themselves. Furthermore, the parameterization of our model has been derived completely independently, without any complex fitting or calibration to the system we aim to describe. The only tuning we have undertaken is that we have somewhat decreased the cost of growth in the DEB model (Campos et al. 2009), so that brown shrimp individuals grow slightly faster, because the maximum possible growth in the original DEB model is less than what has been established experimentally (Hufnagl and Temming 2011a) and measured empirically (Hufnagl and Temming 2011b). Furthermore, we have adjusted environmental productivity (resource renewal rate) so that total annual landings of brown shrimp by the fleet correspond approximately to those observed (30,000 tons). This corresponds in the model to a biomass estimate of large brown shrimp (>5cm) of approximately 18000 tons, or 0.5g/m^2. A recent estimate of the stock of this size range on the basis of the Dutch and German Demersal Fish Survey (DFS) gives a rough estimate of 0.56g/m^2. Brown shrimp resource renewal rate is related to secondary productivity, for which we have empirical estimates (Beukema et al. 1978). However, an unknown fraction of this productivity is suitable and available as food for brown shrimp, while the rest is for example buried deeply in the sediment, or too well-defended (e.g. larger shellfish). In line with these observations, the resource renewal rate we have used is well below that reported for total secondary production (Beukema et al. 1978).

The strongly mechanistic basis of the model and the independently established parameterization, coupled with good correspondence of the dynamics exhibited by the model to that observed, lead us to conclude that the model can be reliably used to estimate the effects of various management scenarios. However, as with any model, it is only valid as long as the assumptions used to construct the model are not violated. Hence, any future scenario studies using this model should always be accompanied by a critical assessment of the validity of the model for such scenarios. For the scenarios studied in this report, the model is appropriate, since studying these scenarios has been the main reason for constructing the model.

We have tested the effects of implementing a 2-step harvest control rule (HCR) which relies on a LPUE threshold value to trigger. For very low values of this threshold, the HCR is never triggered because LPUE never reaches this low value. Such a HCR has zero effect in the current situation, but it should be noted that it can still protect the population from overexploitation in case of an sudden drop of shrimp density, such as may occur in a year with particularly adverse temperature or productivity. Effects of such events are not part of the current modelling exercise. In the model, such an excessively low HCR trigger value is identical to not having an HCR at all, and hence represents the current situation in the field. As the HCR threshold is increased, it starts to have an effect: catches increase and discards are reduced. This is the result of classical growth overfishing, where high fishing mortality leads to that shrimp are caught at relatively small sizes. The effort reduction as a result of the HCR reduces fishing mortality, allowing individual shrimp on average a longer period of growth. This longer growth period more than makes up for the reduced effort, and total landings are higher. At the same time, fewer individuals are caught before attaining commercial size, reducing discards.

At the other extreme, the threshold value is so high that it is essentially ‘always on’. LPUE simply never reaches values above even the lowest HCR threshold (50% of the trigger value). In this situation, effort per ship is maximized at 24 hours per week. Under these conditions, catches are low on the one hand simply because maximum effort is severely reduced, so that a relatively large proportion of shrimp die from background mortality before being harvested. On the other hand, the reduced mortality leads to increased stock abundance, which induces resource competition among brown shrimp. Resource competition in turn leads to slower growth, which leads to smaller shrimp in the stock. Consequently, a smaller proportion of the stock consists of commercial-size biomass. For the same reasons, discards strongly increase under this regime. Another consequence of the 24-hour limit is that mobility of the globally operating vessels is severely restricted. With only 24 hours out of port allowed, they cannot move over longer distances, even if expected LPUE is much better than that in the current location.

It is important to note that this situation, with low harvesting effort, results in very low total mortality for shrimp. This would be a situation which has never occurred since landing data of brown shrimp fishery has been collected (the 1960's). Even though shrimp landings were very small in those early years (ICES 2015), natural mortality was much higher, as the natural predators of brown shrimp were much more abundant. As a consequence, total mortality has not changed very much over the years (Temming and Hufnagl 2015). In other words, even in absence of fishing mortality, brown shrimp have always suffered high mortality, preventing stunted growth. It should hence also be noted that the stunted population does not represent the pristine state of the brown shrimp stock.

In the range of HCR threshold values between these extremes, catch and discards are the result of a mixture of these mechanisms, and the optimum in catches is the optimal balance, where individual shrimp still have enough food to grow at their physiological maximum, while harvesting mortality is low enough that the loss of commercially sized individuals to natural mortality is minimized. This optimum is attained at a total fleet effort substantially lower than the current effort, indicating that this higher yield can be realized at a lower ecological cost in terms of effort-related side effects such as seafloor disturbance, bycatch, fossil fuel usage or disturbance of other wildlife. The optimum yield also coincides with an increased shrimp abundance. Even though such an increase is not necessarily a more natural state (see above), it does reflect a state in which, all else being equal, shrimp fishing mortality is a less important factor in shaping brown shrimp abundance. The effort at optimum yield also leads to a population with a substantially higher fraction of larger (>5cm length) individuals, which does most likely correspond to a more natural situation (because natural mortality is generally biased towards small size). As stated earlier, any model is based on assumptions and may lose its validity when those assumptions are violated. One important assumption we have made is that the parameter values going into the model are, by and large, correct. Because many of these parameters differ between individuals, in time and in space, this is an assumption which is by definition violated. This has important implications for interpretation of the results. The qualitative aspect of the results (the *shape* of the curves in all figures in chapter 0) is largely determined by the mechanisms incorporated in the model, which are derived from first principles and firmly rooted in the laws of physics (most notably, conservation of mass and energy). Uncertainty in parameter values predominantly affects the quantitative aspects, such as where the catch optimum is located (the exact LPUE threshold value and corresponding catch and discards). Hence, the results presented here should not be interpreted as a recipe for manipulating effort to optimize yield, but as a scan of the results possible by implementing a harvest control rule for brown shrimp fishery in the North Sea.

6.2 Answering the main research question

The main research question of this work is formulated as "Is there an ecological need for the management of the thus far mainly unregulated fisheries on brown shrimp in the North sea?"

The work presented here indicates clearly that compared to the current situation, a reduced fishing effort leads not only to a more efficient fishery (higher LPUE), but also to an absolute annual catch increase and reduction of discards of undersized shrimp. Such effort reduction is ecologically desirable because it is associated with reduced bottom disturbance, bycatch of non-target organisms, fossil fuel use and disturbance of other wildlife. Although ultimately the need for management is a societal issue, our results clearly indicate that substantial ecological benefits can be obtained by implementing a harvest control rule for brown shrimp, and that these benefits go hand in hand with higher landings and a more efficient fishing fleet.

6.3 Future prospects

With the ICES advice there is, at least amongst scientist, an international consensus on the advantage, ecologically, of a common European management of North Sea brown shrimp fishing activities. However, despite ICES advice for management of brown shrimp fisheries, consensus among either the member states involved, the industry or other stakeholders is still lacking. This prevents further concrete actions towards the implementation of effective management, as outlined in the ICES advice and the roadmap therein. There appears to be consensus within the industry that an MSC certification is needed, for which the industry is working on a self-management system. Such as system is a challenging task because the fleet is diverse and relatively unorganized. The current work shows clearly how reduced effort leads to higher landings at lower environmental cost. While it is ecologically desirable to reduce impact, higher landings are not necessarily desirable from an economic point of view. Although reduced effort can result in lower cost, the higher landings will negatively affect shrimp prices, making it more difficult for individuals vessels to turn a profit. The current study indicates that the effort reduction can also be attained by reducing the number of vessels, and this will lead also to higher landings. However, these would be shared among fewer vessels, making it easier for vessels to turn a profit despite low prices.

In this study we have mainly focused on the effects of a Harvest Control Rule, as suggested in the ICES road map. However HCR-based management is costly and difficult. It requires a constant monitoring on the LPUEs and ad hoc response to the LPUE if needed. With the current model we could also have a closer look in (the effectiveness of) other ways of management or a combination of measures, like increased mesh size, like recently studied in the German CRANNET project (Schultz et al, 2015), and effort management, which may function equally well, at a fraction of the costs.

The model developed in this study provides a suitable and versatile platform to study a large variety of alternative management scenarios, developments in the fleet, gear innovations and environmental changes. It can hence play an important facilitative role in future discussions regarding brown shrimp fisheries management in the North Sea. Given the importance of international (scientific) consensus, the results of this study will be presented and discussed during de next WGCRAN meeting in spring 2016. Furthermore the industry and IMARES have the intention to organise a stakeholder meeting in 2016 to discuss the results of this study and use them to continue the path towards a more sustainable brown shrimp fishery, here in the Netherlands and international.

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8 Quality Assurance

IMARES utilises an ISO 9001:2008 certified quality management system (certificate number: 124296-2012-AQ-NLD-RvA). This certificate is valid until 15 December 2015. The organisation has been certified since 27 February 2001. The certification was issued by DNV Certification B.V. Furthermore, the chemical laboratory of the Fish Division has NEN-EN-ISO/IEC 17025:2005 accreditation for test laboratories with number L097. This accreditation is valid until 1th of April 2017 and was first issued on 27 March 1997. Accreditation was granted by the Council for Accreditation.

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Justification

Report number: C181/15
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The scientific quality of this report has been peer reviewed by the a colleague scientist and the head of the department of IMARES.

Approved: Prof. Dr. A.D. Rijnsdorp
Senior Researcher

Signature:

Date: 15 December 2015

Approved: Dr. ir. N.A. Steins
Head of fisheries department

Signature:

Date: 15 December 2015

Appendix 1 ICES Advice

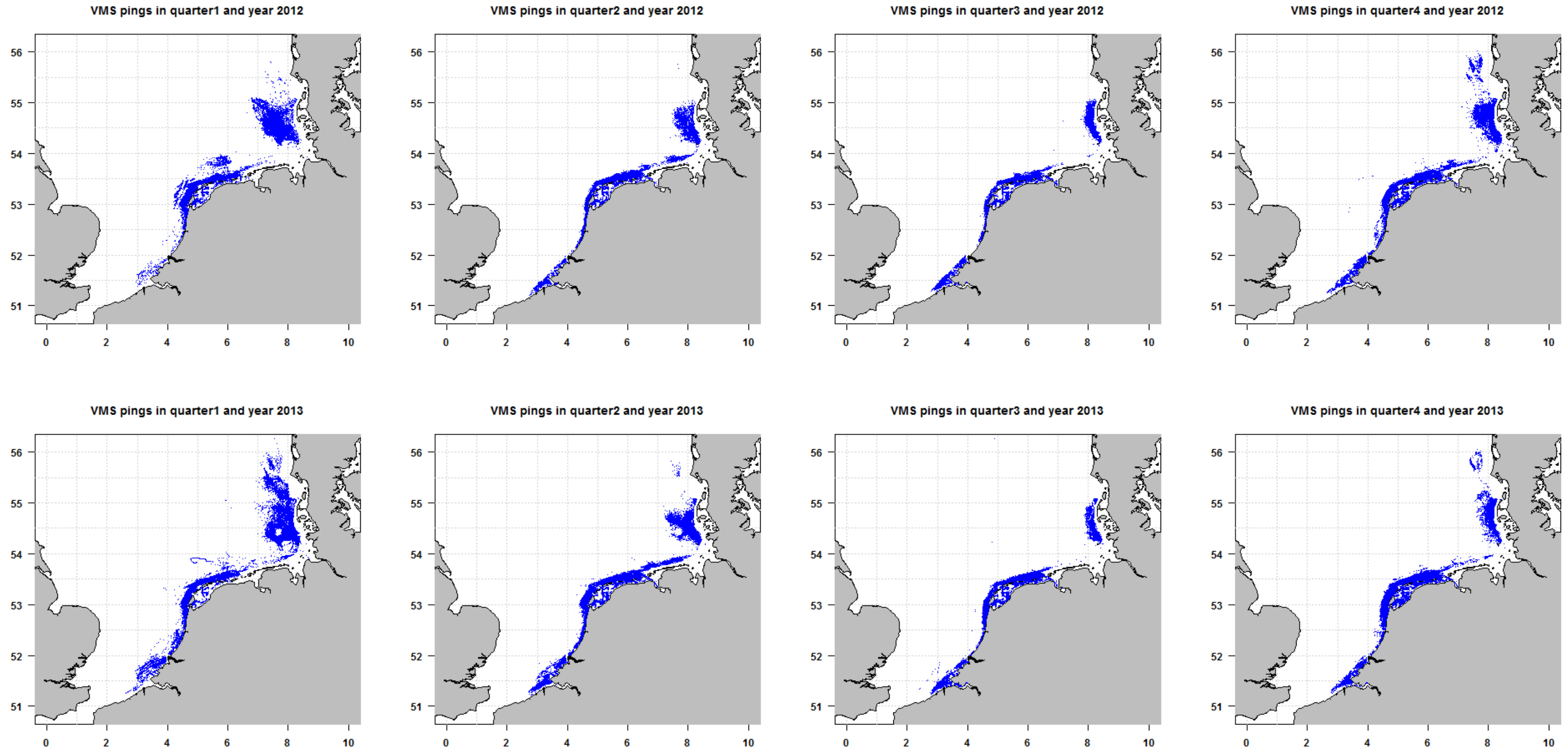
Appendix 2. Interview questions

Introduction to respondent:

This research has the goal to strengthen the model of brown shrimp fisheries that IMARES-colleagues are developing. The model includes information about the ecology of the shrimps and about the behaviour of the fishermen. This interview is about the fisheries behaviour. With key figures and experts we discuss the role of various factors that influence the fisheries behaviour that can be included in the model. We ask respondents to think about the general behaviour of the Dutch brown shrimp fleet. This interview guide is made on the basis of a conversation with the modellers about their assumptions and about the factors that are relevant for their modelling work.

1. What is your role in the Dutch brown shrimp fisheries?
2. Can we speak of different 'groups' of shrimp fishers. If you could divide the Dutch brown shrimp fleet in groups, what would those groups look like. On the basis of which factors do they differ from each other?
3. If shrimp fishers decide if they will go out fishing or not, which factors determine their choice? How does that differ for the different groups defined under Q2?
4. On the basis of what do the fishermen decide where they will fish?
    a. What is the role of other fishermen in this?
    b. What is the role of habit? Are their certain areas where some fishermen always return to, and areas where some fishermen never go to?
    c. To what extent are the fishermen aware of the catches per area of the last week?
    d. One assumption is: a fishermen weighs what he expects to catch in a certain area and what costs he has to made to go to a certain area (fuel, loss in fishing time, ...). On the basis of this he decides what to do. What do you think of this assumption? Does this differ between the groups under Q2?
5. How flexible are fishermen once they are at sea, which factors make them decide to go to a different area?
6. Under which circumstances does a shrimp fisherman stop fishing earlier during his fishing trip?
7. We see in our data how some fishermen arrive in a lot of different harbours during the year. Our assumption was that this is the group of fishermen that varies most in fishing areas and that the fishermen who do not vary so much between arrival harbours always go back to the same fishing areas. What do you think of this assumption? How would you explain the differences between these groups?
8. How many foreign/flag shrimp cutters fish in Dutch shrimping areas?
    a. Where do they come from?
    b. Where do they fish?
    c. How do they fish?
9. This model is developed in order to test management scenarios. Which scenario would you like to test?
10. Do you have anything to add?

Appendix 3. Quarterly spatial distribution of VMS locations of brown shrimp fisheries in 2012 and 2013.



Appendix 4: data selection for Figure 13 and Figure 14.

See for general dataset processing the materials and method section in chapter 4 (4.1.2). Globally operating vessels are defined as the 12 vessels that have the highest number of unique arrival harbours (Figure 2). Dutch Wadden Sea vessels are the 12 vessels that are most active in the Dutch Wadden Sea, with 98% of their fishing activity or more in the Dutch Wadden Sea.

Fleet effort graph:
Fishing trip length for trips conducted in 2011-2013 (data base file: 2010-2013) is determined as number of days away from port. The average trip length of the 12 global vessels and 12 Dutch Wadden Sea vessels is calculated per week and plotted over the years.

LPUE graph:
Brown shrimp LPUE for trips conducted in 2011-2013 (data base file: 2010-2013) was determined as landings quantity (kg) divided by the multiplication of engine power and days away from port (kWday). The average LPUE of the 12 global vessels and 12 Dutch Wadden Sea vessels is calculated per week and plotted over the years.