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PhD thesis

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1. Preface

1.1 Summary

Accounting for the interactions and effects of fisheries targeting multiple species is a longstanding issue in management systems using single species quota allocations as output control of fish stocks, such as in the European Union (EU). An unfortuante sideeffect of such management is discarding, which is the act of returning catches to the sea for one or several reasons, including insufficient quota. To minimize discarding, the EU has gradually implemented a regulation making it mandatory for fishers to take (most) catches to port. This landing obligation aim at ending discards for most fisheries and fish stocks and at incentivising fishers to increase their selectivity. For mixed fisheries, the landing obligation has thus increased the importance of catch composition (the mix of species caught together), because the regulation takes away the mechanism by which fishers previously dealt with mismatches between quota allocations and actual catches in mixed fisheries; discarding. How to adapt the fisheries and fisheries control to the landing obligation is a question of practical options at-sea but also what expectations key stakeholders have to the landing obligation and how much they are ready to comply with it. In line with the intention of the landing obligation, improved selectivity is the main option for fishers to adapt to the landing obligation. Together with increased gear selectivity, increased spatial selectivity by identifying the spatial and temporal occurrences of unwanted catches are options for optimising the fishing effort to best target wanted catches and thereby increase selectivity. However, the current fisheries management and data collection systems in Europe do not include full coverage of at-sea fishing operations. New technologies like electronic monitoring with video (EM) and opportunistic data collected at-sea may provide the additional information necessary to address the fine-scale adaptations required to improve spatial selectivity. At the same time, these new technologies may well provide a better data basis to provide the scientific advice for the management of the European fisheries.

This PhD investigated the expectations of Danish fishers and fishery inspectors towards the landing obligation, as well their opinions on EM as a compliance tool in the fisheries (Paper I). We found that the landing obligation is perceived as difficult to enforce by fishery inspectors and that the majority of fishers are negative or indifferent towards the landing obligation. We found that fishery inspectors favour at-sea monitoring and observers over EM but that EM in general is seen as an option among fishery inspectors to ensure compliance with the landing obligation. Fishers have a more negative opinion towards EM, although this is mainly the case for fishers with no experience of having EM on-board, whereas the majority of fishers with experience with EM are positive towards EM.

As mentioned above, improved spatial selectivity is one of the main options for adapting to the landing obligation. Adding new data to the existing sources of fisheries dependent data, like on-board observers, logbooks and vessel monitoring systems, could potentially provide new opportunities for improving the daily fishery tactics of where and when to fish. During this PhD, a new source of fisheries dependent data already existing in the Danish fisheries came to our attention. This data source, called SIF, "*Sporbarhed I Fiskerisektoren*" [traceability in the fisheries sector] collects information on retained catches packed at-sea from on-board grading machines. The system is used for traceability requirements, where fishers pack and label their fish at-sea (sea-packing) which ensures buyers of the fish that the crates holding the fish are labelled correctly. In terms of information level, this voluntary system resembles what is already required in the electronic logbooks (which are mandatory for vessels above 12 meters in length). However,

where logbooks for catch information record only the species and volume landed, SIF also records the size (commercial size categories) of the landed fish. As such, the spatial distribution of fish sizes can be extracted. Fish size is an important driver in fishing tactics because minimum sizes determine whether fish can be sold for human consumption and because for most species, the prices per kg are higher for fish with a larger body size. This sea-packing data has to our knowledge never been used for scientific purposes. Therefore, this PhD investigated the coverage and reliability of data from the vessels which sea-pack and use the SIF system (Paper II). It was found that the validity of sea-packing data in the SIF system is not only vessel specific; it can also vary depending on the species. No clear factors were found that could explain these variations. If using SIF as scientific data input, one has to validate the quality of the data for each vessel and species for which the analysis is to be run.
Unlike the SIF system, EM is established as a control tool in the United States and Canada and European trials have used EM for several management purposes. Based on data from the largest and longest running Danish EM trial, the reliability and cost of EM was investigated (Paper III). It was found that the reliability of EM in the Danish trial has been increased by technical developments and simple practical fixes. This underpin EM as a feasible Monitoring, Control and Surveillance (MCS) tool. While automated image analysis is currently the main development, which can lower EM costs, it was found that video audit times and the corresponding running costs of EM have already decreased by optimising video audit routines. EM is not a silver bullet that by default is the optimal solution for compliance or data collection, but it is a cost-effective measure compared to the current alternatives like on-board observers or at-sea control. Finally, the analysed sea-packing and EM data was used as case study input to a book chapter as part of the Horizon 2020 project “DiscardLess” (Book chapter I). The aim of these case studies was to present support tools to fishers, which may assist them in optimising their spatial selectivity.

In conclusion, EM and traceability systems like SIF do provide opportunities for improved data in fisheries management and fisheries science. Within the context of the landing obligation, EM and traceability systems has a dual applicability. On one hand, these systems can assists fishers with additional information to adjust their fishery and increase selectivity. On the other hand, these systems can be used as a control tool. The acceptance of such systems rely much on how they are used. While this is a policy decision, science plays an important role in advising decision makers and stakeholders. Bringing the work of this PhD into the advisory sphere and future publications is the next stage for my work on SIF and EM.

1.2 Popular science summary

The effects of fisheries targeting multiple species are receiving an increased attention in fisheries management, not least in the European Union where a discard ban (called “landing obligation”) was introduced with the 2013 Common Fisheries Policy. Commercial fishing vessels operate in a quota system in the European Union. It is often a challenge to catch the entire allocated quota for each targeted species while avoiding over-quota catches of some species in mixed fisheries. The most limiting quota risks becoming the actual overall quota cap for the mixed fishery (the so-called “choke species” effect) because these over-quota catches can no longer be discarded, leading to a loss in quota usage and profit.
The aims of this project are to examine fisheries dependent data from traceability systems, including electronic monitoring with video and to investigate possible applications of these systems. Additionally, fishers’ and relevant stakeholders’ perspectives on the European landing obligation and use of electronic monitoring with video was investigated. Explorative methods for spatial selectivity to mitigate the effect of unwanted catches in mixed fisheries in the North Sea and Skagerrak is examined.

Electronic monitoring and traceability systems do provide opportunities for improved data in fisheries management and fisheries science. Within the context of the landing obligation, these systems has a dual applicability. On one hand, they can assists fishers with additional information to adjust their fishery and increase selectivity. On the other hand, these systems can be used as a control tool. The acceptance of such systems rely much on how they are used and science plays an important role in advising decision makers and stakeholders to use electronic monitoring and traceability systems in manner that benefit all.

1.3 Populærvidenskabeligt resume

Effekten af fiskeri målrettet flere arter har i stigende grad fået opmærksomhed inden for fiskeriforvaltningen, ikke mindst i EU, på grund af målene i den fælles fiskeripolitik fra 2013. Denne politik omfatter en ”landingsforpligtigelse”, hvilket betød en gradvis indførsel af et forbud mod genudsætning (discard) i fiskeriet. I EU forvaltes det kommercielle fiskeri igennem et kvotesystem. Dette giver ofte udfordringer, især i blandet fiskeri, når de enkelte fiskere forsøger at fange hele den tildelte kvote for hver målart, samtidig med, at de skal undgå at overskride deres tildelte kvote for andre arter. Tidligere kunne fangster der overskred den tildelte kvote genudsættes, men dette er ikke længere lovligt med den nye landingsforpligtigelse. Herved risikerer den mest begrænsende kvote at fungere som flaskehals og blive den egentlige eller realiserede kvote for det blandede fiskeri på grund af den såkaldte ”choke”-effekt, hvilket fører til et tab i kvoteudnyttelse og fortjeneste.

Formålene med dette projekt er at undersøge fiskeriafhængige data fra sporbarhedssystemer, herunder kamerasystemer, og undersøge mulige anvendelser af disse systemer samt sammenligne nuværende fiskeridatasæt med data fra sporbarhedssystemer. Yderligere undersøges fiskernes og fiskerikontrollørernes mening vedrørende landingsforpligtelsen og brug af kameradokumentation i fiskeriet. Tilgange til rumlig selektivitet, som et redskab til at mindske omfanget af uønskede fangster i det blandede fiskeri i Nordsøen og Skagerrak, undersøges ligeledes.

Sporbarhedssystemer og kameradokumentation giver muligheder for at forbedre datamængden inden for fiskeriforvaltning og fiskerividenskab. I forhold til landingsforpligtelsen har disse systemer en dobbelt anvendelses mulighed. På den ene side kan de hjælpe fiskere ved at give yderligere oplysninger, som kan bruges til at justere fiskeriet og øge selektiviteten. På den anden side kan disse systemer bruges som et kontrolværktøj. Accepten af sådanne systemer i fiskeriet er afhængig af, hvordan de anvendes i sidste ende, og her spiller videnskaben en vigtig rolle ved at rådgive beslutningstagere og interessenter i brugen af kameradokumentation og sporbarhedssystemer på en måde, som er til gavn for alle involverede parter.

1.4 Acknowledgements

The present thesis is submitted in partial fulfilment of the requirements for obtaining a Doctor of Philosophy (Ph.D.) degree. The thesis consists of a synthesis, a supporting book chapter and three supporting papers. The book chapter is peer-reviewed and published by Springer while the three papers are published in peer-reviewed journals.

I wish to express my sincere gratitude to my supervisors: Professor Clara Ulrich, Professor J. Rasmus Nielsen and Senior Researcher François Bastardie from the Technical University of Denmark – National Institute of Aquatic Resources (DTU AQUA).

I would also like to express a special thanks to Jesper Bech Eiersted, Lars Olof Mortensen, Heiðrikur Bergsson, Erling Larsen, Mogens Schou and Carsten Søndergaard Pedersen for their contributions and help to the thesis. Further, I would like to thank all my colleagues at DTU AQUA for many inspiring talks and discussions.

Fishers and video auditors, too numerous to mention individually, undertook a lot of the at-sea collection of the data used in this dissertation as part of the Danish traceability system, “Sporbarhed I Fiskerisektoren” (SIF) and the Cod Catch Quota Management trial (CCQM). I owe a debt of gratitude to Carsten Søndergaard Pedersen for helping me access the SIF data and Jesper Bech Eiersted for facilitating contact to Danish fishery inspectors. The support from Kirsten Birch Håkansson, Josefine Egekvist and Jeppe Olsen for extraction of logbook data to run analyses and comparison with SIF and CCQM data has been and is valued as well. Without this data access, this dissertation would not exist.

Last but not least, I would like to thank my wife Kim for her support. Not only in general, but also very hands-on with helping in the extraction of SIF data, first manually and later by development of a web scraper.

The financial support granted by the European Commission as part of the Horizon 2020 Programme under grant agreement DiscardLess number 633680 and from the EASME project DRuMFISH contract number EASME/EMFF/2014/1.3.2.4/ SI2.721116 to conduct the research described in the supporting papers is greatly acknowledged.

Kongens Lyngby, October 2019

Kristian Schreiber Plet-Hansen

1.5 List of PhD publications

Paper I	**Plet-Hansen, K.S**., Eliasen, S.Q., Mortensen, L.O., Bergsson, H., Olesen, H.J., Ulrich, C., 2017. Remote Electronic Monitoring and the Landing Obligation – some insights into fishers' and fishery inspectors' opinions. Mar. Policy 76, 98–106. https://doi.org/10.1016/j.marpol.2016.11.028
Paper II	**Plet-Hansen, K.S**., Larsen, E., Mortensen, L.O., Nielsen, J.R., Ulrich, C., 2018. Unravelling the scientific potential of high resolution fishery data. Aquat. Living Resour. 31, 14 pp. https://doi.org/10.1051/alr/2018016
Paper III	**Plet-Hansen, K.S**., Bergsson, H., Ulrich, C., 2019. More data for the money: Improvements in design and cost efficiency of electronic monitoring in the Danish cod catch quota management trial. Fish. Res. 215, 114–122. https://doi.org/10.1016/j.fishres.2019.03.009
Book chapter I	The best way to reduce discards is by not catching them! Reid, D. G.; Calderwood, J.; Afonso, P.; Bourdaud, P. ; Fauconnet, L.; González-Irusta, J. M. ; Mortensen, L. O.; Ordines, F.; Lehuta, S.; Pawlowski, L.; **Plet-Hansen, K. S.**; Redford, Z.; Robert, M.; Rochet, M.-J.; Rueda, L.; Ulrich, C.; Vermard, Y., 2019. The European Landing Obligation: Reducing Discards in Complex, Multi-Species and Multi-Jurisdictional Fisheries. ed. / Sven Sebastian Uhlmann; Clara Ulrich; Steven J. Kennelly. Springer Open, 2019. p. 257-278.

1.6 Other publications during PhD

Book chapter A1	Tools and technologies for the monitoring, control and surveillance of unwanted catches. James, K. M.; Campbell, N.; Viðarsson, J. R. ; Vilas, C.; **Plet-Hansen, K. S.**; Borges, L.; González, Ó.; van Helmond, A. T. M.; Pérez-Martín, R. I.; Antelo, L. T.; Pérez-Bouzada, J.; Ulrich, C., 2019. The European Landing Obligation: Reducing discards in complex, multi-species multi-jurisdictional fisheries. ed. / S. Uhlmann; C. Ulrich; S. Kennely. Springer Open, 2019. p. 363-383.
Paper A2	van Helmond, A., Mortensen, L.O., **Plet-Hansen, K.S**., Ulrich, C., Needle, C.L., Oesterwind, D., Kindt-Larsen, L., Catchpole, T., Mangi, S., Zimmermann, C., Olesen, H.J., Bailey, N., Bergsson, H., Dalskov, J., Elson, J., Hosken, M., Poos, J.J., *In Press*. Electronic Monitoring in Fisheries: Lessons from global experiences and future opportunities. Fish Fish.

1.7 List of conference presentations during PhD

Presentation	Improving fisheries science with high resolution commercial fishery data. **Plet-Hansen, K. S.**; Mortensen, L. O.; Nielsen, J. R.; Larsen, E.; Ulrich, C., 2017. Oral presentation, ICES ASC 2017, Fort Lauderdale, United States.
Presentation	Trade-off between value of landings and discard impact. **Plet-Hansen, K. S.**; Ulrich, C., 2018. Oral presentation, IIFET 2018, Seattle, United States.
Presentation	Fine-scale information on discard occurrence and catch composition by coupling EM and sea-packing commercial fishery data. **Plet-Hansen, K. S.**; Nielsen, J. R.; Ulrich, C., 2018. Oral presentation, ICES ASC 2018, Hamburg, Germany.

1.8 List of ICES Working Groups during PhD

Working Group on Mixed Fisheries Methods (WGMIXFISH-METH)	IFREMER, Nantes, France 2017
Working Group on Technology Integration for Fishery-Dependent Data (WGTIFD)	ICES, Copenhagen, Denmark 2019

1.9 List of abbreviations

AIS Automatic Identification System

AUC Area Under the Curve

CFP Common Fisheries Policy (of the European Union)

CQM Catch Quota Management

CCQM Cod Catch Quota Management trial

DFAD Danish Fisheries Analyses Database

DFPO *Danmarks Fiskeriforening Producent Organisation* (Danish Fishermen's Association)

EBM Ecosystem Based Management

EEZ Exclusive Economic Zone

eLog Electronic Logbook

EM Electronic monitoring with video (same as remote electronic monitoring)

EU European Union

FAO Food and Agriculture Organization (of the United Nations)

FDF Fully Documented Fisheries

GIS Geographical Information Systems

GES Good Environmental Status

GPS Global Positioning System

ICES International Council for the Exploration of the Sea

IFREMER Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER) (English: French Research Institute for Exploitation of the Sea)

IMO International Maritime Organization

ITQ Individual Transferable Quota

MAUP Modifiable Areal Unit Problem

MCS Monitoring, Control, Surveillance

MCRS Minimum Conservation Reference Size

MLS Minimum Landing Size

MS Member State (of the EU)

MSC Marine Stewardship Council

MSFD Marine Strategy Framework Directive

MSY Maximum Sustainable Yield

NSAC North Sea Advisory Council

RTCs Real Time Closure zones

SDM Species Distribution Model

SIF *Sporbarhed I Fiskerisektoren* (Traceability In the Fisheries Sector)

SPAEF SPAtial EFfieciency metric

STECF Scientific, Technical and Economic Committee for Fisheries

TAC Total Allowable Catch

UK United Kingdom

VDEC Vessels Data Exchange Center

VMS Vessel Monitoring Systems

1.10 Glossary

Choke species	A species for which the available quota is exhausted (long) before the quotas are exhausted of (some of) the other species that are caught together in a (mixed) fishery (Zimmermann *et al*., 2015).
Catch	What is caught with a fishing gear. Catch = Landings + Discards
Discards	Catch returned to the sea. Discards = Catch - Landings
Landings	Catch taken ashore. Landing = Catch - Discards
Landing Obligation	Regulation stated in Article 15 of the Common Fisheries Policy of the European Union. The regulation makes it mandatory to bring all catches ashore, unless the catch is covered by an exemption.
High-grading	Discarding of catch that should be landed in the hope of replacing this with a more valuable catch later
Fully Documented Fisheries	A fishery in which detailed information on where the fishery is carried out, on the gear used, on the quantities of catches per day is recorded and verified by one or more independent systems
Maximum sustainable yield	The largest catch amount that can be extracted without leading to a collapse in the exploited population in the long-term
Relative Stability	Allocation key or principle used to distribute EU fishing opportunities to EU member states
Sea-packing	Gutting, icing and packing fish intended for landing in crates at-sea
Selectivity, gear	Avoiding unwanted catches by adaption of the fishing gear and/or increasing wanted catches by gear modifications
Selectivity, spatial	Avoidance of unwanted catches by movement in space (and time) and/or increasing wanted catches by targeting areas where catch composition is better

2. Introduction

Accounting for the interactions and effects of fisheries targeting multiple species is a longstanding issue in management systems using single species quota allocations as output control for fish stocks, such as in the European Union (EU). The implementation of the landing obligation has increased the importance of these interactions, as the regulation has taken away a vent for dealing with mismatches between quota allocations in mixed fisheries; discarding. How to adapt the fisheries and fisheries control to this new management is a question of practical options at-sea but also a question of what expectations key stakeholders have to the landing obligation. Together with increased gear selectivity, increased spatial selectivity by identification of the spatial and temporal occurrences of unwanted catches are options for optimising the fishing effort to best target wanted catches. However, the current fisheries management and data collection systems in Europe do not include full coverage of at-sea fishing operations. Electronic monitoring with video (EM) and opportunistic data collected at-sea may provide the additional information necessary to address the fine-scale adaptations needed to improve spatial selectivity. Additionally, such new technologies may well provide an opportunity for better data to advise the management of the European fisheries. In the following sections, this PhD will present the background and management framework of the European landing obligation. Then it will introduce considerations on the importance of fish body size, on social aspects relevant for the landing obligation and will present fishery-dependent data sources currently in use as well as under trial. Finally, this will be related to spatial considerations relevant for spatial selectivity and to possible future reflections regarding spatial fisheries management (Fig. 1).

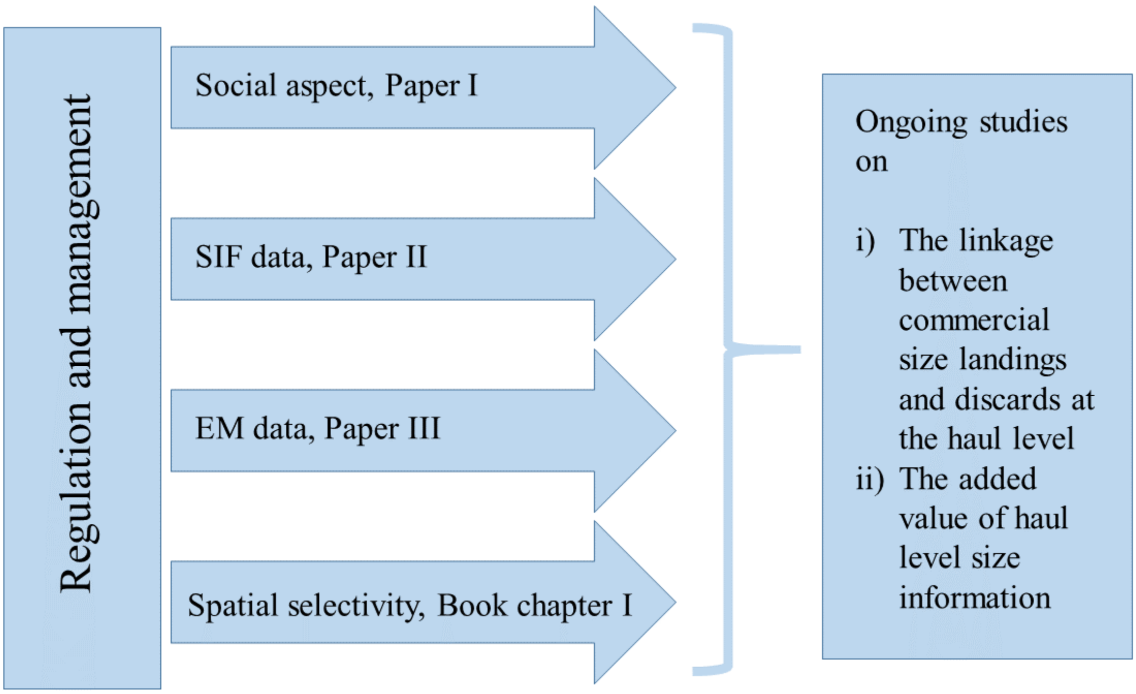

Figure 1. Conceptual overview of PhD publications and continuous work.

This PhD covers the findings from the following four publications:

1. Inquiry on the perception among Danish fishers and fishery inspectors regarding the implementation of the European landing obligation, including possible compliance measures (Paper I, Plet-Hansen *et al*., 2017)
2. Validation of a new fisheries dependent dataset from the Danish fishing fleet that have not been used for scientific purposes before (Paper II, Plet-Hansen *et al*., 2018)
3. Investigation of electronic monitoring (EM) data and EM system setup for selected fish species in the North Sea and Skagerrak (Paper III, Plet-Hansen *et al*., 2019)
4. Exploration of potential usages of above mentioned data sources as a support tool for fishers when optimising their spatial selectivity (Book chapter I, Reid *et al*., 2019).

A short overview of each of these publications is given in grey boxes in the relevant sections of the synthesis, together with some explanations on the underlying context and work performed ("The making of").

2.1 Background

”Managing fisheries is managing people” (Hilborn, 2007a). This statement is at the core of fisheries management and resonates in introductory fisheries management courses and up to the top level setting of management strategies. The objective of fisheries management is to ensure that biological, social or economic benefits can be derived from the fishery while avoiding undesirable effects caused by the exploitation such as stock collapse, habitat degradation, economic deficient or social costs (Jennings *et al*., 2001a). The 20th century saw several examples of stock collapses, with arguably the most famous being the collapse of the Canadian cod fishery in 1992, raising awareness on the impact of fishing and resulting in increased public management of the fisheries (Botsford *et al*., 1997; Jennings *et al*., 2001a). Globally, well-managed fisheries with stock assessments are considered to be in better condition and generating better yield than poorly managed fisheries (Costello *et al*., 2012; Raakjær, 2009a). In order to succeed, fisheries management has to encompass complex and dynamic environmental, economic, social and political processes, which will differ across fisheries, not only at national, but also at regional and local levels (Bradley *et al*., 2019; Hilborn, 2007a). For the fisheries management to succeed, knowledge on how, why, when and where fisheries are conducted and on the resulting impacts is essential (Clark *et al*., 2007), not only for the specific management of fisheries but also to inform fisheries science and advice (Bradley *et al*., 2019; Hilborn and Ovando, 2014; Salomon and Holm-Müller, 2013). In Europe, scientific advice, including stock assessment, is provided by the International Council for the Exploration of the Seas (ICES) (ICES, 2019a). To provide stock assessments, both fishery-independent data, like scientific survey data, and fishery-dependent data, like declaration of landings and fishing effort, are needed to estimate the trend in stock abundance (Jennings *et al*., 2001d). However, for stock assessments to be as reliable and precise as possible, the quality and availability of input data must be high, which can be a challenge to achieve for fishery-dependent data (Cotter and Pilling, 2007; Hedley *et al*., 2015), for several reasons. These include but are not limited to: i) the non-random nature of fishing operations (Cheung *et al*., 2012; Reid *et al*., 2019; van Helmond *et al*., 2016). ii) inadequate or wrongful self-reporting (Hedley *et al*., 2015; Mangi *et al*., 2016). iii) low and potentially biased coverage of monitoring programmes like on-board observers (Benoît and Allard, 2009; Depestele *et al*., 2011; Mangi *et al*., 2016).

Assessing the fishing mortality induced on the fished stocks and the amount of harvested individuals should account not only for the landed individuals, but also for those returned to the sea, i.e. the discarded catch (Jennings *et al*., 2001c; Kelleher, 2005; Zeller *et al*., 2017). The discarded catch is defined by the Food and Agriculture Organization of the United Nations is:

“*That portion of the catch returned to the sea as a result of economic, legal, or personal considerations.*” (Alverson *et al*., 1994).

The drivers behind discarding are multiple and diverse. They include reasons like catch comprising of incidental bycatch, catch under minimum sizes, prohibited species, low market demand, non-commercial species, species with low quota allocated or high-grading, which is the act of discarding fish of small size, hence low value, in the hope of catching larger and thereby more valuable fish later (Batsleer *et al*., 2015; Sigurðardóttir *et al*., 2015; Vázquez-Rowe, *et al*, 2011). While some discarded specimens may survive handling, others and potentially all, will not (Damalas, 2015; Kindt-Larsen *et al*., 2011; Rihan *et al*., 2019). The main source of discard estimates going into the stock assessment in Europe comes from observer programmes which only monitor a small share (around 1%) of the fishing activities (Benoît and Allard, 2009; Depestele *et al*., 2011; Kelleher, 2005; Poos *et al*., 2013; Valentinsson *et al*., 2019). Extrapolation from such a small coverage is problematic, not only because of the risk of missing rare events but also because of the high variability in the amount and composition of catches between fishing trips and hauls as well as between fishing vessels (Evans and Molony, 2011; Sims *et al*., 2008; Valentinsson *et al*., 2019). In addition, fishers may adapt their fishing operations depending on the presence of observers, an effect known as the "Hawthorne effect" within sociology or as the "observer effect" within fisheries (Gale, 2004; James *et al*., 2019; Schaeffer and Hoffman, 2002). Furthermore, the complexity in drivers of discarding means that any assessment of measures to reduce discards or adaptations to reduce unwanted catches needs to be based on substantial and reliable data (Batsleer *et al*., 2015; Catchpole *et al*., 2005; Crean and Symes, 1994; Feekings *et al*., 2012; Little *et al*., 2015; Reid *et al*., 2019).

The EU has put discarding practices and mitigation measures against these at the core of the European fisheries management, through the obligation to account for and land (most) catches included in Article 15 in the 2013 CFP (EU, 2013; Salomon *et al*., 2014).

In the following, a short introduction to the history of discarding in the EU and the drivers behind is presented.

2.2 Management regime and legal context

Fishing in the Exclusive Economic Zone (EEZ) of an EU member state and fishing undertaken by EU vessels outside EU waters are managed by the Common Fisheries Policy (CFP) (Sobrino and Sobrido, 2017). In the latter case, the management takes place with respect to and in collaboration with relevant third countries' management regime (EU, 2013), e.g. when EU vessels fish in Norwegian waters. The establishment of a common EU fisheries legislative framework was a process closely linked to the developments in international fisheries laws, including the establishment of EEZs, and the negotiations between the founding EU states and Denmark, Ireland, Norway and the United Kingdom (UK) prior to and after the first EU enlargement in 1973 (Havstein, 2013; Raakjær, 2009a). One of the most difficult negotiations was to agree on principles for the sharing of fishing opportunities, and it was not until 1983 that the CFP could be established for all EU member states' fisheries and waters (Raakjær, 2009a; Sobrino and Sobrido, 2017). An important element in the negotiations was the concept of *Relative Stability*, which in essence is that each EU member state is ensured a certain share of the fishing opportunities of each fish stock (Sissenwine and Symes, 2007; Sobrino and Sobrido, 2017). This is based on historical catch records, regional dependency on fishery in accordance with the "Hague Resolution" and fishing rights lost due to the creation of EEZs (EC, 1976; Sissenwine and Symes, 2007; Sobrino and Sobrido, 2017). Later enlargements of the EU, including the accession of major fishing nations like Portugal and Spain, had to respect and take into account the established *Relative Stability* among other EU members states during the accession negotiations (Raakjær, 2009a; Sobrino and Sobrido, 2017).

Since its establishment in 1983, the CFP has been revised three times (in 1992, 2002 and 2013). Discard practices have been raised as an issue of concern every time, but not deemed as a serious problem in the pre-revision communications prior to each reform. Rather, discarding has been viewed as an unfortunate but unavoidable practice (Borges, 2015; Borges and Penas Lado, 2019). Prior to the last revision of the CFP in 2013 for example, the European Commission issued a Green Paper (EC, 2009) pointing to five key failings of the 2002 CFP which the 2013 revision should aim at mitigating. Quoting:

- *"a deep-rooted problem of fleet overcapacity;*
- *imprecise policy objectives resulting in insufficient guidance for decisions and implementation;*
- *a decision-making system that encourages a short-term focus;*
- *a framework that does not give sufficient responsibility to the industry;*
- *lack of political will to ensure compliance and poor compliance by the industry.*"
  (EC, 2009).

Literature criticizing the 2002 CFP for incentivizing unsustainable fishing practices is abundant (Daw and Gray, 2005; Hatcher, 2013; Khalilian *et al*., 2010; Kraak *et al*., 2013; Msomphora and Aanesen, 2015; Petter Johnsen and Eliasen, 2011; Raakjær, 2009b; Reiss *et al*., 2010; Salomon *et al*., 2014; Salomon and Holm-Müller, 2013; Sissenwine and Symes, 2007; Symes and Hoefnagel, 2010). Among the shortcomings of the CFP, high fishing mortality due to discarding and the inherent conflict between *Relative Stability* and well-balanced fishing opportunities based on present conditions were pointed to (Borges, 2015; Crean and Symes, 1994). An issue raised was that fishers saw it as being morally wrong that they were forced to discard viable fish only because of quota regulations (Nielsen and Mathiesen, 2003). Yet, it looked as if the 2013 CFP revision would not specifically address the discard issue (Borges and Penas Lado, 2019; Fitzpatrick *et al*., 2019). This however, was to change with the filming of a British fishing vessel discarding large quantities of good, large fish after re-entry into EU EEZ from the Norwegian EEZ in 2008 (Borges, 2015; Borges and Penas Lado, 2019). Norway implemented its first discard ban in 1987 (Gullestad *et al*., 2015; Karp *et al*., 2019), but because discarding was legal in EU waters, the practice among EU vessels was to re-enter EU EEZ after fishing in Norwegian EEZ and then dump the catch intended for discard taken in the Norwegian EEZ. The absurdity in this was quite palpable and caused significant public awareness and call for action against discarding in the EU (Borges, 2015; van Hoof *et al*., 2019). In response to this, the European Council began public discussions on the proposed reform of the CFP (van Hoof *et al*., 2019). Public pressure gained increased momentum in 2011, with the launch of the TV show and campaign known as "Hugh's Fish Fight" led by the British chef and journalist Hugh Fearnley-Whittingstall (Fernley-Whittingstall, 2014; van Hoof *et al*., 2019). The campaign gained substantial support, collecting more than 800,000 signatures for a petition to end discards, and put large public pressure on the EU and on member states to revise the fisheries management system to promote sustainable fisheries and end discarding (Borges, 2015; Borges and Penas Lado, 2019; Fitzpatrick *et al*., 2019). The result was that the idea of a discard ban emerged again, late into the political process of the CFP revision (van Hoof *et al*., 2019). The 2013 CFP revision includes an alternative version to a discard ban, positively baptized "landing obligation" (EU, 2013; van Hoof *et al*., 2019) which aim at increasing selectivity and reduce unwanted catches (Hedley *et al*., 2015; van Hoof *et al*., 2019). To control the landing obligation, Article 15 in the CFP lists on-board observers, electronic monitoring (EM) and "others" and state that member states shall respect the principle of efficiency and proportionality while ensuring detailed and accurate documentation (EU, 2013).

The first fisheries became subject to the landing obligation on 1 January 2015. These were pelagic fisheries and certain species (herring, sprat, salmon and cod) in the Baltic Sea (EU, 2013; NaturErhvervstyrelsen, 2014; Poos *et al*., 2018; Salomon *et al*., 2014). On 1 January 2019, all species regulated by Total Allowable Catch (TAC) or a Minimum Conservation Reference Size (MCRS) within EU jurisdiction became subjected to the landing obligation (EU, 2013; Salomon *et al*., 2014). The TACs are allocated by the EU to its member states using quotas. The member state then distributes this to its fishing fleet (Frost and Hoff, 2017). MCRS was adopted as a term to replace Minimum Landing Size (MLS) after the introduction of the landing obligation. Where MLS defined the minimum size for when a fish could be landed, MCRS define the minimum size for when a fish can be sold for human consumption, as all fish must be landed with the landing obligation (Borges and Penas Lado, 2019).
The introduction of the landing obligation marks a paradigm shift in the European fisheries management, as this changes the focus of management efforts towards the full catch (Mortensen *et al*., 2017b, 2015; Uhlmann *et al*., 2019). If all catches are taken ashore, discarding would no longer occur and landings would be equal to the catch. That is, instead of having a landings based quota management system, a catch quota management system will in effect be in place when catches must be landed (Batsleer *et al*., 2015; Kindt-Larsen *et al*., 2011; Ulrich, 2016). As part of this, TACs have been increased for stocks when these have become covered by the landing obligation. The reason for these so-called TAC top-ups is based on the assumption that the previously discarded amount of fish can be added to the TAC, because all non-exempted catches are taken ashore (Borges and Penas Lado, 2019; Stockhausen, 2019). While catch quota management can be said to be in place for stocks covered by the landing obligation, this is not the case for the following exemptions that the landing obligation allow for (EU, 2013):

i) Only species with a TAC or a MCRS are subject to the landing obligation. For example flounder (*Platichthys flesus*) in the Baltic Sea is exempted (Poos *et al*., 2018). This has triggered a drive to verify the relevance of TACs in the management of a number of bycatch stocks (ICES, 2018a). Indeed, for dab (*Limanda limanda*) and flounder in the North Sea, the management response to fulfil the criteria set by the landing obligation has been to remove the TAC, whereby the landing obligation do not apply to these species. The species thereby continue to be caught and discarded as bycatch (Borges and Penas Lado, 2019).

ii) Prohibited species are not subject to the landing obligation. While it seems prudent not to bring prohibited species ashore, the implication of this is that prohibited species continue to be discarded with no direct incentive to increase selectivity, just like for bycatch without a TAC or MCRS. Prohibited species include a range of ray and shark species such as starry ray (*Amblyraja radiata*), basking shark (*Cetorhinus maximus*) and porbeagle (*Lamna nasus*) (EU, 2015). Perhaps more importantly, some species has changed status to prohibited species, whereby they are exempted from the landing obligation, leading to continuation of some legal discarding. This is the case for picked dogfish (*Squalus acanthias*) (Borges and Penas Lado, 2019) and eastern Baltic cod (EC, 2019a, 2019b; Our Fish, 2019).

iii) If a species in a fishery has a high survivability after discarding according to scientific advice, the species can be exempted from the landing obligation within the specific fishery. Again, as with the exemption for prohibited species, it does make sense not to bring a fish ashore to die, if it could have survived by being released back to sea. However, survivability may change depending on numerous factors such as time of day, capture depth, time on deck and condition of fish prior to capture, all in all making it challenging to set a clear limit for survivability exemptions, although guidelines have been developed to ensure a common protocol for performing the scientific survivability studies (ICES, 2018b; Rihan *et al*., 2019; Stockhausen, 2019).

iv) The *de minimis* exemptions. In essence, this exemption applies if increased selectivity in a fishery is too difficult to achieve according to scientific advice or if the cost of handling and bringing the unwanted catches ashore are deemed too high to justify the landing obligation. In such a case, up to 5% of catches of the specific species can be discarded but these discards must be recorded and will count against the TAC. The *de minimis* does therefore not allow a higher fishing mortality, as the full catch will still be subtracted from the TAC. Rather, it allows for a certain flexibility in storage and associated induced costs of having to land unwanted catches (Rihan *et al*., 2019; Stockhausen, 2019; van Hoof *et al*., 2019).

v) Fish damaged by predators. If for instance a seal has been eating from catches of cod in a gillnet, whereby these catches have virtually zero market value due to predator damage, these catches can be discarded and will not be subtracted from the TAC. However, no definition exists of what damage is (extent or cause) and neither of predators or how compliance is to be ensured (Stockhausen, 2019).

While these exemptions may mitigate its impact for certain fisheries, the landing obligation has not been welcomed by European fishers (de Vos *et al*., 2016; Fauconnet *et al*., 2019; Plet-Hansen *et al*., 2017; van Hoof *et al*., 2019). The regulation in itself is seen by many fishers as contradictory because while it is true that many fish may die from discarding, it is also true that taking fish to shore that would have been discarded otherwise will for certain kill all of the fish (Plet-Hansen *et al*., 2017; Sigurðardóttir *et al*., 2015; van Hoof *et al*., 2019). Furthermore, the feeling of being excluded from the decision process and the likely economic losses from the regulation have further reduced the acceptance (de Vos *et al*., 2016; Hoff *et al*., 2019; Raakjær, 2009c; Villasante *et al*., 2016). Another concern, in particular for mixed fisheries, is the "choke species" (Fitzpatrick *et al*., 2019; Karp *et al*., 2019). Quoting Zimmermann's definition:
"*A choke species is a species for which the available quota is exhausted (long) before the quotas are exhausted of (some of) the other species that are caught together in a (mixed) fishery*" (Zimmermann *et al*., 2015).
This challenge arises when the quota allocation for a species turns out to be disproportionate to the quota allocations and actual catches for other species associated with the given fishery. The effect is that the fishers have to stop fishing for their remaining quotas on other species because they have no quota left for the choke species and therefore violate the landing obligation if they catch more. Prior to the landing obligation, such mismatch was dealt with by discarding the species that would otherwise choke the fishery (Hedley *et al*., 2015; Kraak and Hart, 2019). To illustrate the issue, a simple example with two stocks (Species A and B) and three model scenarios of the mixed fisheries model *Fcube* (Ulrich *et al*., 2011) is presented in Fig. 2. This approach has been used by ICES since 2009 (ICES, 2017) to provide advice on mixed-fisheries issues, to warn on risks of TAC overshooting and discards increase if TACs of various stocks jointly caught are not aligned, and to explore maximum sustainable yield (MSY) ranges rather than single-point MSY as a management approach (Rindorf *et al*.,2016). The scenarios are: i) max. Fishers will continue to fish until all quota or fishing opportunity has been exhausted, ii) min. Fishers will stop fishing as soon as the limiting quota (choke species) is reached, iii) value. Fishers will fish with an effort where they best balance the value between the stocks in the mixed fisheries scenario.

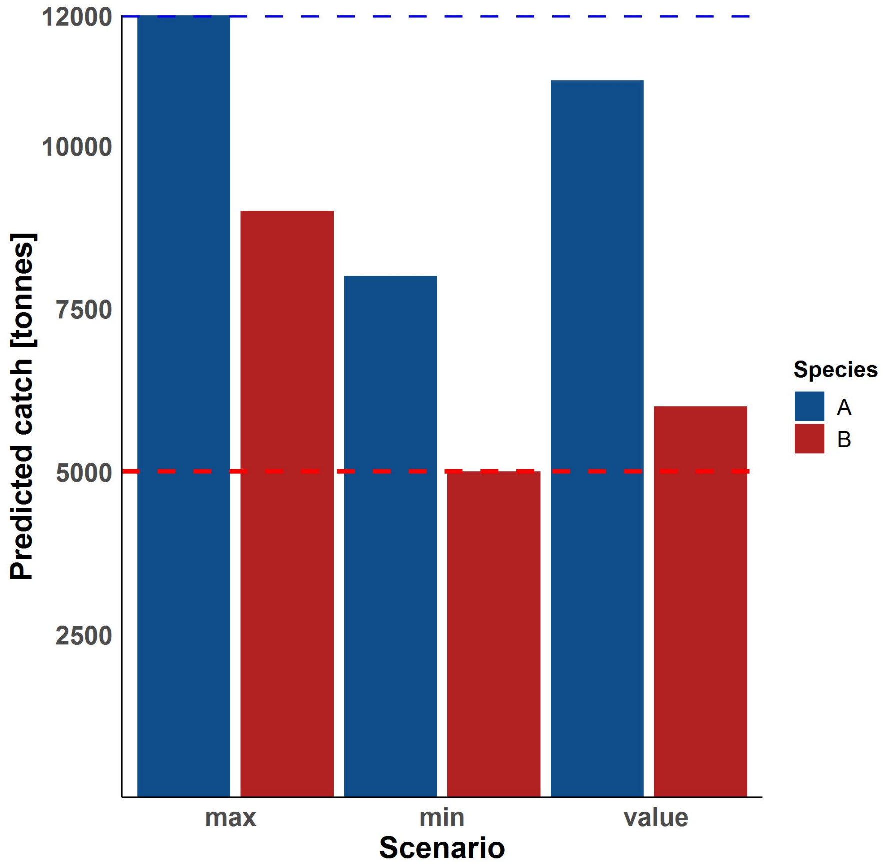

Figure 2. Simple mixed fisheries scenario overview. Blue horizontal line correspond to the TAC for Species A (12,000 tonnes) and red horizontal line correspond to the TAC for Species B (5,000 tonnes).

In this illustration, Species B is the limiting stock. In the max-scenario, fishers are predicted to overshoot the TAC for species B by 4,000 tonnes. In the min-scenario, fishers are predicted to underutilize the TAC for species A with 4,000 tonnes. In the value-scenario, fishers are predicted to overshoot the TAC for species B by 1,000 tonnes and underutilize the TAC for species A by 1,000 tonnes.

While the choke issue is mainly thought of as a TAC/quota restriction issue (Catchpole *et al*., 2017; Karp *et al*., 2019; Zimmermann *et al*., 2015), the challenge to the fishers is in fact more complicated than this. Because of low price, some species may choke vessels' fishing opportunities at the level of individual fishing trips by filling up storage capacity with low value fish that has to be taken ashore which hereby reduce the profit or may even make the fishing trip unprofitable (Hoff *et al*., 2019; NSAC, 2017). Taking this into account and because of the *Relative Stability* and national quota allocations, the North Sea Advisory Council (NSAC) categorized four types of chokes. Quoting:

*"**Category 1:** Sufficient quota at MS level—choke is due to distribution within the Member State such that a region or fleet segment does not have enough and this can be resolved by the Member State itself.*

***Category 2:** Sufficient quota at EU level, but insufficient quota at MS level—choke is due to a mis-match of catches and the distribution of quotas between Member States and can theoretically be resolved between themselves in a regional context.*

Category 3: *Insufficient quota at EU level—choke is due to insufficient quota within the relevant sea basin to cover present catches or catch levels that can be realistically reduced, resulting in a total stop of fishing for a Member State or Member States.*

(…)

Category 4: *Economic choking may occur at the vessel level when there is a considerable bycatch of a low value species and the boat is filled with fish that will not deliver a profit."* (NSAC, 2017)

Denmark allocates and manages its quota allocations with an Individual Transferable Quota (ITQ) system. Danish fishers have thus the opportunity to acquire additional quota from other Danish fishers (Andersen *et al*., 2010). This provides more flexibility when dealing with Category 1 choke situations than what would have been the case if the quota system was non-transferable as in other EU member states such as France and Spain (Frost and Hoff, 2017; Hoff *et al*., 2019; Larsen *et al*., 2013). However, depending on the price of acquiring additional quota, this option may still lead to an economic loss, as quota prices fluctuate according to supply and demand (Branch, 2009; Mortensen *et al*., 2018; Probst, 2019). While the ITQ system allows more flexibility for Danish fishers, this does not mean that Danish fishers may simply trade their way out of choke issues, both because of the impact on the profitability of the fishery and because of the three remaining choke categories. Hake (*Merluccius merluccius*) largely encompasses all these three choke categories for the Danish mixed demersal fisheries in the North Sea. As Category 2, hake biomass in the North Sea is increasing rapidly, whereby the actual available biomass and thereby TAC may be underestimated because of the time lag in stock assessments, where historical trend lines are used to estimate the biomass of the stocks (Baudron and Fernandes, 2015; Kraak *et al*., 2013). As Category 3, historical catches of hake were low in the North Sea when catch shares were allocated within EU member states, leading to a relatively low hake TAC for member states like Denmark, Germany and the Netherlands compared to France or Spain (Baudron and Fernandes, 2015). Finally as Category 4, the price per kg of hake is generally lower than for instance for cod and haddock, and the fish has a tendency to be damaged during the haul which further reduces its sale value (Catchpole *et al*., 2018; Plet-Hansen *et al*., 2019).

Increasing selectivity to reduce unwanted catches, as was the intention with the landing obligation (Hedley *et al*., 2015; van Hoof *et al*., 2019), is the main adaptation strategy (Fitzpatrick *et al*., 2019). There are many options to increase selectivity, falling within two overall categories: gear selectivity and spatial selectivity (O'Neill *et al*., 2019; Reid *et al*., 2019). This thesis focuses on the latter, with a more specific focus on the requirement for fishery-dependent data to inform it. Knowledge on spatial selectivity is important not only in the context of the landing obligation, but also in the context of ecosystem based management (EBM) as detailed in the following paragraph.

2.3 Fish body size distribution

The move towards EBM, calling for a more holistic fisheries management than the traditional single species approach, means that interactions between species and individuals must be taken into account (Burgess *et al*., 2016; Pikitch *et al*., 2004). The need to move towards such management is widely recognized (Baudron *et al*. 2019; Burgess *et al*., 2016; Hilborn, 2011; Pikitch *et al*., 2004; Piet *et al*., 2019; Trenkel, 2018; Ulrich *et al*., 2012). Integrating EBM indicators and parameters into existing management models through input from end-to-end ecosystem models, economic or bio-economic models is not only valuable as a management tool, but is indeed needed to support EU directives like the Marine Strategy Framework Directive (MSFD) (Bossier *et al*. 2018; Nielsen *et al*. 2018; Baudron *et al*. 2019). The MSFD aims at achieving Good Environmental Status (GES) for all

EU waters by 2020 (EU, 2008a). To measure this, qualitative descriptors are listed in Annex 1 of the MSFD, with descriptor 3 and 4 stating:

"(3) Populations of all commercially exploited fish and shellfish are within safe biological limits, exhibiting a population age and size distribution that is indicative of a healthy stock.

(4) All elements of the marine food webs, to the extent that they are known, occur at normal abundance and diversity and levels capable of ensuring the long-term abundance of the species and the retention of their full reproductive capacity." (EU, 2008a).

This means that the exploited stocks must not be exposed to a fishing pressure higher than the one ensuring exploitation at MSY, but also that the age and size composition of the stock must also include both small and large individuals. More and better knowledge and data related to size and species distribution and abundance is needed, to assist in model calibration and development, to account for potential density-dependent effects, and to estimate size-related effects of fishing on fished stocks (Bossier *et al*., 2018; Nielsen *et al*., 2018; van Gemert and Andersen, 2018; Vasilakopoulos *et al*., 2016).

While the importance of maintaining a balanced size distribution has been emphasised by the MSFD, specimen size has always been important to fishers directly. Not only are fishers managed by MLS, termed MCRS in the EU (EU, 2013; Froese *et al*., 2008; Karp *et al*., 2019) but market preferences create higher prices per kg depending on size (Branch, 2009; Graham *et al*., 2007; Stratoudakis *et al*., 1998; Villasante *et al*., 2019). With the implementation of the landing obligation, the incentive for increased selectivity translate into spatial avoidance as well as gear adaptations, and thereby avoidance tactics that require more knowledge of species and size distribution (Little *et al*., 2015; Reid *et al*., 2019). Furthermore, for managers to monitor selective adaptations to the landing obligation, length or size based indicators have been pointed to as necessary indicators by the Scientific, Technical and Economic Committee for Fisheries (STECF) (STECF, 2018a). In short, while size has been important in fisheries and fisheries management for decades, the objectives of the CFP and MSFD have only added to the importance.

2.4 The social aspect – compliance

As stated in Section 2.1, the low coverage of observers' data in Europe is problematic because of the lack of detailed knowledge on actual working conditions at-sea (Benoît and Allard, 2009; Depestele *et al*., 2011; Valentinsson *et al*., 2019). While this is not a new issue, the landing obligation has increased its importance (Kraak and Hart, 2019). Prior to the landing obligation, discarding was legal - as long as the discarding was not due to high-grading (Batsleer *et al*., 2015) - and the fishing mortality caused by discarding could be estimated from observer data (Mangi *et al*., 2015). However, when discarding is by default illegal, there is an increased risk of fishers changing their behaviour in the presence of observers – the "observer effect" (James *et al*., 2019; Schaeffer and Hoffman, 2002) – or may be less inclined to accept observers (Kraak and Hart, 2019; Valentinsson *et al*., 2019). This happens despite the fact that in the EU observers are deployed on vessels for scientific purposes only, and not for control as for instance in the United States (Little *et al*., 2015; Mangi *et al*., 2015; Uhlmann *et al*., 2013). Because of this potential bias the trustworthiness of observers' data can be questioned (Cotter and Pilling, 2007), but the implications may be even larger. Regulations seen as illegitimate and with low compliance may lead to a shift in the social norms among fishers with increasing non-compliance as a result, not only for the specific regulation but in general (Nielsen, 2003; Nielsen and Mathiesen, 2003). Research, inquiries and meetings with European fishers have shown that the legitimacy of the landing obligation is perceived so poor that the risk for such as shift is real (Catchpole *et al*., 2018; Condie *et al*., 2014a; Kraak *et al*., 2016; Plet-Hansen *et al*., 2017), see also Box 2.1 and 2.2. Fully documented fisheries (FDF), where the entire catch is reported and verified, for instance by means of electronic monitoring with video (EM) or full observer coverage (described in section 3), is an option to ensure compliance (James *et al*., 2019; Kraak and Hart, 2019; Little *et al*., 2015, Ulrich *et al*., 2015). Beyond the fact that such control measures will come with costs, political and ethical considerations need to be considered as well (Nielsen and Mathiesen, 2003; Sutinen and Kuperan, 1999). A top-down approach where full observers or EM coverage is imposed will likely meet strong opposition (Hedley *et al*., 2015; Mangi *et al*., 2015). Obtaining 100% compliance solely by stricter control is likely not possible and it is even questionable whether such an approach is desirable, for instance because this may well be perceived as a top-down implementation (Hedley *et al*., 2015; Nielsen and Mathiesen, 2003; Mangi *et al*., 2015). Instead, creating appropriate incentives and using control measures to verify compliance could be a more efficient approach (Kraak *et al*., 2016; Nielsen and Mathiesen, 2003; Sutinen and Andersen, 1985; Sutinen and Kuperan, 1999). Some European fishers have been reported to accept EM under certain conditions, but it is important for acceptance that an equal playing field is kept among fishers and nations (Catchpole *et al*., 2018; Plet-Hansen *et al*., 2017). That is, increased monitoring has to be distributed evenly across fisheries and member states to avoid unfair competition (Catchpole *et al*., 2018; Condie *et al*., 2014b; Dalskov *et al*., 2012). Opposition towards full monitoring will remain but will likely be less if fishers are integrated into the process through co-management, as industry perspectives and practical issues can be accounted for in the process (Kraak *et al*., 2016; Kraak and Hart, 2019; Mangi *et al*., 2015; Raakjær, 2009c; Sigurðardóttir *et al*., 2015; Sutinen and Kuperan, 1999).

Box 2.1. Paper I, short summary.

(Plet-Hansen *et al*., 2017).

To shed light on the perspectives and expectations of two key stakeholders impacted by the landing obligation, questionnaire surveys were performed among fishers and fishery inspectors in Denmark. Fishery inspectors were positive or neither for, nor against the use of electronic monitoring (EM) and ranked on-board observers, at-sea control and EM as the three best options to ensure compliance with the landing obligation. More than 80% of fishery inspectors pointed to enforcement of the landing obligation as the main challenge. Fishers did not expect a positive effect of the landing obligation, neither for the environment or the fisheries, and fishers did in general not see the justification for the landing obligation. Fishers experienced with EM where more positive towards EM as a control tool than fishers with no experience with EM.

Table 5
Challenges for the fishery control with the landing obligation.

		Fishery inspectors (n=30)	
Question	Answers	N	%
What do you see as the primary challenge regarding the landing obligation, for the fisheries control? (open ended question)	Enforcing the landing obligation	25	83.3
	Getting the fishers to see why the landing obligation is meaningful	3	10.0
	No new challenges	1	3.3
	Did not answer	1	3.3

Table 5 in Plet-Hansen et al., 2017. Challenges for the fishery control with the landing obligation.

Incentives could be ease of technical regulations, the *quid-pro-quo* approach where the TAC top-ups given due to the landing obligation is only given to vessels with full documentation of zero discards (Kraak *et al*., 2016) or real-time spatial management to avoid unwanted catches (Little *et al*., 2015) are specific benefits that FDF could allow for. These are already implemented in other parts of the world such as the United States and Canada (Karp *et al*., 2019; Little *et al*., 2015; McElderry, 2008).

2.5 The social aspect – collaboration

Stakeholders' involvement has been highlighted as a necessity to facilitate a collaborative approach in fisheries management (de Vos *et al*., 2016; Kempf *et al*., 2016; Marchal *et al*., 2016; Raakjær, 2009c). This is not an easy task because different stakeholders have different objectives driving their view on the usage of the marine environment, e.g. creating jobs, provide economic growth or environmental protection. Besides the more obvious conflicting objectives, such as environmentalists vs. bottom trawlers or oilrigs, stakeholders with more similar objectives may also be in conflict, such as conflicts between different fishers or even countries because of negative impacts of one activity (Hilborn, 2007b; Kempf *et al*., 2016; van Gemert and Andersen, 2018). For example, fishery for forage fish has cascading effects on their predators (Dickey-Collas *et al*., 2013). Stakeholders' involvement and collaboration can occur at an institutional level, such as at the design of management plans, setting of TACs or closure zones, drafting of technical regulations and so forth (Condie *et al*., 2014b; Gullestad *et al*., 2015; Karp *et al*., 2019; Marchal *et al*., 2016). At the institutional level, the involvement of fisher and environmental representatives is in place in the EU through Advisory Councils (ACs) which the European Commission consults with during management processes related to the CFP (Carpenter *et al*., 2016; Marchal *et al*., 2016). Collaborative approaches are not limited to the institutional level. In the United States, quota pools and spatial management is a mean to reduce bycatch by increasing data sharing among fishing vessels, and by using a private third party to collect and analyse the data collected from observers and vessels (Little *et al*., 2015; S. Martell, Sea State Inc., personal communication). Direct sharing of information to avoid visiting poor fishing grounds also exist between vessels in Danish waters, although the quality and information detail is lower than in the US example (Eliasen and Bichel, 2016; Little *et al*., 2015). Examples of scientists collaborating with fishers are numerous, e.g. where fishers' knowledge acquired by experience and the empirical scientific approach is merged to carry out trials to increase gear selectivity, document spatial avoidance possibilities, document the amount of bycatch and identify issues arising from regulations (Kindt-Larsen *et al*., 2012; Mortensen *et al*., 2018, 2017a; O'Neill *et al*., 2019; Reid *et al*., 2019).

Of specific relevance to this thesis, the collaboration between fishers, the Danish Fisheries Agency (the agency which the Danish fisheries control is organised under), and DTU AQUA has led to the collection of highly detailed EM data (Dalskov *et al*., 2012; Plet-Hansen *et al*., 2019; Ulrich *et al*., 2015, 2013), see also Box 3.3 and 3.4. Trust is essential for such data sharing between fishers and scientists (and/or managers) (Kraak and Hart, 2019; Mangi *et al*., 2015). While this is true for the examples cited above, this is possibly even more the case for the "*Sporbarhed I Fiskerisektoren*" (SIF) sea-packing data presented in this thesis (Box 3.1 and 3.2), as fishers received no direct benefit, such as quota uplifts, for this data share.

Box 2.2. The making of Paper I.
(Plet-Hansen *et al.*, 2017).
The first fisheries became subject to the European landing obligation in 2015. The effect of the new regulation, both regarding the practical implications for the individual vessel and regarding rule compliance, was under much speculation as the landing obligation was phased in. Stakeholder perspectives and expectations for the landing obligation could point at issues which fisheries scientists should investigate mitigation tools for, for instance through the EU Horizon 2020 project "DiscardLess".

The two key stakeholders, Danish fishers and fishery inspectors, were asked to fill in questionnaires or were interviewed. Questions were designed to get responses on their expectations and opinions regarding the landing obligation as well as on the use of Electronic monitoring (EM). Questions were mainly overlapping between fishers and fishery inspectors, but specific questions were designed to capture explicit topics only applicable to the work of one group or the other. Fishers were either interviewed face to face or by telephone in order to get sufficient responses from both EM experienced and non-EM experienced fishers as it was hypothesised that the opinion towards EM might differ between these. After talks with the head of the control section at the Danish Fisheries Agency it was possible to conduct a nationwide survey among fishery inspectors with questionnaires distributed by email.
Although the number of surveyed fishers was too low to represent a nationwide survey for this stakeholder group, the number of interviewed EM experienced fishers was high enough to be representative of this specific group of fishers. Contrasting EM experienced and non-EM experienced fishers' responses together with that of fishery inspectors does therefore capture certain aspects where division or overlap in opinion seems evident. For instance, more than half of the EM-experienced fishers were positive towards EM as a Monitoring, Control and Surveillance (MCS) tool, while 90% of non-EM experienced fishers were against EM.

3. Fishery-dependent data sources

Overall, fishery dependent data can be grouped into effort data and catch data (Jennings *et al*. 2001d). Effort data contain information on vessels' engine power, gear type, positional and temporal data of placement of gear. Fishing gears cover a wide array of nets, pots, dredges and lines to name a few but overall gear types are divided into two categories: Passive and active. Passive gear types rely on the target species moving into the gear. Examples are gillnets, pots and long-lines. Active gear types are towed through the water to catch the target species and fishing operations are typically termed hauls or tows. Examples are trawls, dredges and purse seiners (EU, 2016b; Jennings *et al*., 2001b). The focus of this PhD is on trawlers whereby the term haul will often be used to describe fishing operations.

Catch data contain information on the amount of fish caught per species including parameters such as size, length or age composition of the catch. However, only landings and not actual catch data is reported fleet or fishery wide in the EU (Cotter and Pilling 2007; James *et al*. 2019; Mangi *et al*. 2015). Therefore, landings data contain information on the fraction of the fish, which is caught and taken ashore only. To be truly catch data, the dataset must contain not only information on the landings but also on the fraction of the fish that is caught and returned to the sea, also known as the discard fraction. In this section a short overview of selected sources for fishery-dependent data is given (Table 1).

Table 1 – Overview of presented fishery-dependent data collection systems. Table is inspired by the ICES Working Group on Technology Integration for Fishery-Dependent Data (WGTIFD), which I participated in (ICES, 2019b). *Considerable parts of this PhD's findings went into the first year report as DTU AQUA's contribution to the working group. I; independent of fishers, S; self-reported by the fishers, -; not recorded by system.*

Monitoring objective	**Data Element**	**System**							
		Sales slips	*Log-book*	*VMS/ AIS*	*Observers*	*EM*	*SIF*	*VDEC*	*Yellow notes*
Vessel identification	*Vessel ID*	S	S	I	I	I	S	S	S
Trip Information	*Temporal trip information*	-	S	I	I	I	S	S	S
	Non-fishing spatial trip information	-	-	I	I	I	-	-	-
	Management Area	S	S	I	I	I	S	S	S
Fishing activity	*Temporal*	-	S	I	I	I	S	S	-
	Spatial	-	S	I	I	I	S	S	-
	Gear	-	S	-	I	I	S	S	S
Landings	*Amount*	I	S	-	I	(I)	S	S	S
	Species	I	S	-	I	(I)	S	S	S
	Size classes	I	-	-	I	(I)	S	S	S
Discards	*Amount*	-	S	-	I	I	S	S	-
	Species composition	-	S	-	I	I	S	S	-
	Size composition	-	-	-	I	I	-	-	-
Protected species	*Species*	-	S	-	I	I	-	S	-
	Handling	-	S	-	I	I	-	S	-
Biological data	*Length*	-	-	-	I	I	-	-	-
	Sex	-	-	-	I	-	-	-	-
	Condition	-	-	-	I	(I)	-	-	-
	Tissue sampling)	-	-	-	I	-	-	-	-

3.1 Sales slips

Sales slips or sales notes record the landings of fish. Records include several market descriptors such as tax identification number and name of the buyer (EU, 2009). From a biological perspective, the main information recorded in the sale slips are the weight of each species and the commercial size class. Sales slips are recorded at landing and report therefore for the entire trip, meaning that the information level can be detailed to individual vessel and management area, e.g. IVb for the central North Sea (EU, 1996; Hedley *et al.*, 2015). As such, detailed haul-by-haul information such as haul location for vessels with active gears or species composition is not available (Batsleer *et al.*, 2015; Mortensen *et al.*, 2017a).

3.2 Logbooks

Commercial fishers in the EU operating vessels at or above 10 meters in length are required to declare the (live) weight of their landings per species, management area and gear. For vessels at or above 12 meters in length, the logbook must be in an electronic format (eLog) (EU, 2016a; 2011). Since 2015, landings in weight should be reported for each haul and as a minimum once every 24 hours (EU, 2012; Miljø- og Fødevareministeriet, 2014). Additionally, discards of a species amounting to more than 50 kg (live weight) on a trip must be reported in the logbooks (EU, 2009), but this reporting has previously not been considered to occur at a trustworthy level (Hedley *et al*., 2015) and it is therefore uncertain whether this information is reliable.

3.3 Vessel monitoring systems and automatic identification system

Vessel monitoring systems (VMS) are on-board devices that collect and use satellite transmission to relay the time and position from GPS as well as speed and course of the vessel at a predefined time interval to relevant authorities (EU, 2019, 2011). VMS are in place several places in the world, e.g. the United States (Muench *et al*., 2018), Taiwan (Chang *et al*., 2014), Norway (Skaar *et al*., 2011) and Australia (Deng *et al*., 2005). In EU, all vessels above 12 meters in length must have a VMS device in operation (EU, 2019, 2011). The relay of the position of fishing vessels can be used directly as a Monitoring, Control, Surveillance (MCS) tool to avoid fishing activities in closed areas (James *et al*., 2019). Additionally, information on course and speed of the vessel allows the reconstruction of vessel trajectories and thereby the estimation of fishing pressure exerted on the seabed by gear types like bottom trawls (Hintzen *et al*., 2018, 2010). Mapping the catch reported in the eLog can be obtained by coupling eLog data with VMS (Bastardie *et al*., 2010; Hintzen *et al*., 2012; James *et al*., 2019). However, the catch recording in the eLog is weight by species, meaning that the fish size composition of the recorded species is not available at the haul level. The fish size composition of the catch is not recorded until the sales slips are filled out when the vessels offload in port. This size composition can be redistributed back to the VMS-logbook data (Bastardie *et al*., 2010) but under the assumption that the fish size distribution of the landings at the fishing trip level is the same as the fish size distribution of the landings at the haul level. Depending on the spatio-temporal extent of the fishing trip as well as the number of hauls conducted during the fishing trip, this assumption is likely less accurate for some vessels compared to others. Automatic identification system (AIS) is another on-board device that records and relays the time and position as well as course and speed of vessels. AIS differ from VMS by being developed for navigational and security purposes (Gerritsen *et al*., 2013; Girard and Du Payrat, 2017; IMO, 2019) and AIS data is recorded at much shorter intervals compared to VMS (minutes rather than hours) (Gerritsen *et al*., 2013; Girard and Du Payrat, 2017; Kroodsma *et al*., 2018). AIS is mandatory for vessels of certain sizes, depending on area and vessel type (IMO, 2019; Søfartsstyrelsen, 2019). In the EU, fishing vessels above 15 meters in length are required to adhere to class A AIS, while vessels below 15 meters may carry class B AIS or no equipment (EU, 2019, 2011). The difference between class A and B is the frequency of transmission, with class B being lower (but still more frequent than VMS). Additionally, vessels using class A AIS equipment may turn off information transmitted by class B carrying vessels, to avoid overloading their display at the bridge (Søfartsstyrelsen, 2019). While the AIS data provide an opportunity to conduct finer-scale spatial analysis of fisheries (Kroodsma *et al*., 2018), the usage of AIS for other purposes than the original navigational and security purposes is controversial. The reason is that while the data is publicly available, the International Maritime Organization, which has put the requirements for AIS into force, opposes the free publication of AIS data. The concern is that other usages than the original intended may lead to declining acceptance of AIS, which in turn may lead to vessels turning off or tampering with the equipment (Girard and Du Payrat, 2017; IMO, 2019).

3.4 On-board observers

The use of on-board observers is literally the presence of at least one observer on-board commercial fishing vessels, whose task is to collect scientific data and/or to ensure compliance with management regulations (James *et al*., 2019). In some fisheries, 100% observer coverage is mandatory and observers are deployed to ensure compliance and to collect data used to minimize unwanted fishing activities, e.g. by setting Real Time Closure zones (RTCs) based on information on vessels' bycatch levels and positions. An example of such a program is the United States' Alaskan eastern Bering Sea pollock fishery, where the private company Sea State Inc. collects observers' data and set up RTCs which the fishing vessels must respect in order to gain access to a bycatch quota pool (Little *et al*., 2015). In the EU it is mandatory for vessels to take observers on-board, unless the vessels are unfit, e.g. due to space limitations or similar practical issues which mean that the working conditions for the observer is too poor (EU, 2008b). In practice, permission by the skipper was the norm before observers would embark on a fishing trip with a vessel. However, the implementation of the landing obligation has led to stricter practices in some EU member states because of increased refusal to take on observers (STECF, 2016; Valentinsson *et al*., 2019). In the EU, observers are not used for enforcement but only for the collection of scientific data such as length, weight, age, tissue and otoliths samples as well as landings and discards (James *et al*., 2019; Mangi *et al*., 2015; Uhlmann *et al*., 2013). In spite of this scientific role only, the issue of observers' refusal is likely because discarding (of TAC species) has become an illegal activity under the landing obligation, which was not necessarily the case prior to the landing obligation (Valentinsson *et al*., 2019). EU observers' data is collected by sampling as much of the catch from as many hauls occurring at the observed fishing trip as possible. In the best case, the species composition is determined and weighed for the full catch, protected species are registered, marine litter, otoliths to age the fish are taken from discards and the fish body lengths are measured for discards and landings (Håkansson, 2019; Hansen, 2019; Uhlmann *et al*., 2013). However, due to the amount of catches, it is frequent that random subsamples of the catch (including the catch destined to be discarded) is taken from as many hauls as possible during the observed fishing trip. The priority lies in getting observations from as many hauls as possible rather than having everything collected from a fewer number of hauls (Hansen, 2019). The total discard of the individual haul is then estimated by calculating the discard ratio for the subsamples. To estimate the total discarded amount of the fishing fleet, the estimated discard ratio for the fishing trips with observers on-board is then multiplied to the reported landings (ICES, 2010, 2013; Pennino *et al*., 2014). However, as mentioned in section 2.1, the accuracy of such extrapolation can be questioned.

3.5 Vessels data exchange center and yellow catch information notes

The vessels data exchange center (VDEC) system and the yellow catch information notes were developed to comply with EU standards on traceability (EU, 2009, 2002). The yellow catch information notes were developed by the Danish fishing industry for small-scale vessels while VDEC was developed by the company Anchor Lab K/S and the Technical University of Denmark. The yellow notes state the Vessel ID, name of the skipper, date of first and last catch, geographical area of the catch as ICES subdivision, EEZ, gear type and whether the vessel is MSC-certified (Marine Stewardship Council certification). The notes are placed with the landings in fish crates which are also labelled with the species and commercial size class whereby the minimum labelling and information requirements are complied with (Dandanell and Vejrup, 2013; EU, 2011, 2009, 2001) (Fig. 3).

VDEC is capable of delivering more detailed data than the yellow catch information notes or the eLog, including crate catch composition, MSC register, and commercial size classes. However, because minimum reporting requirements proved to be less extensive than originally expected, most of the data reported by the fishers is today reduced to haul position, time, and non-sized catch information (O. Skov, co-founder of Anchor Lab K/S, personal communication). The crude information resolution of the yellow catch information notes and the manner in which VDEC is used in practice mean that these systems do not provide new fisheries-dependent data because the information level is similar or higher in the logbooks. Rather, VDEC and yellow catch information notes are sources for food traceability and economic information, which may not be available for certain (mainly small-scale) vessels through other data sources.

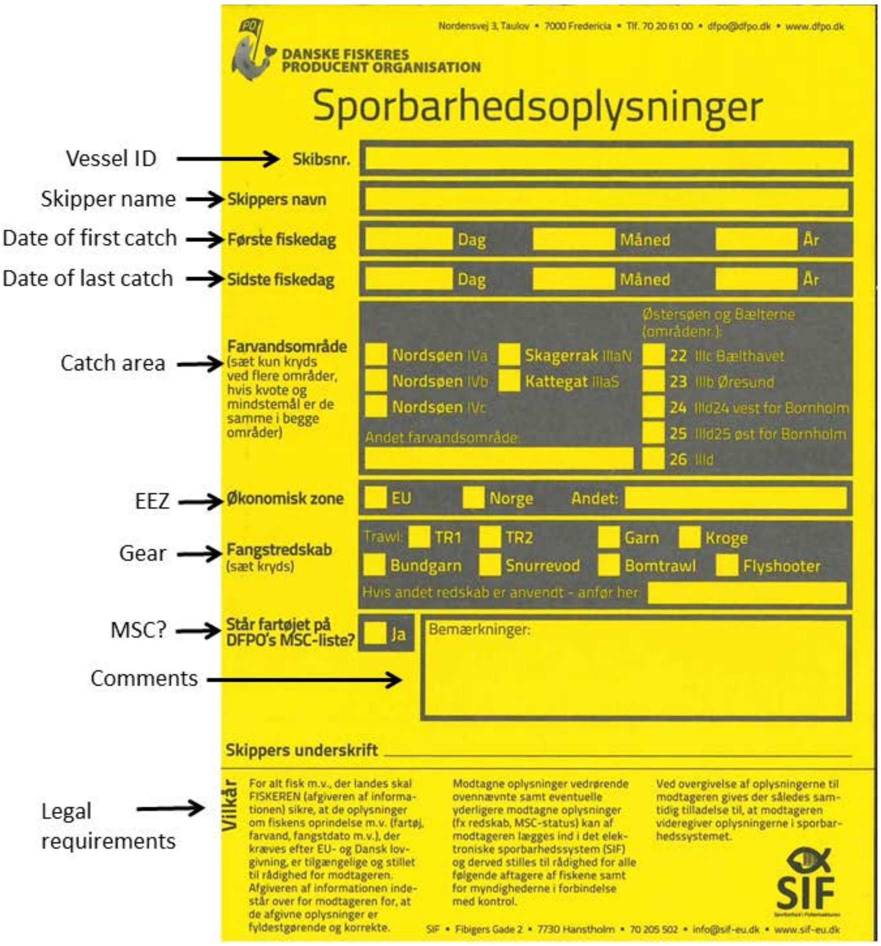

Figure 3. Yellow catch information note.

3.6. Sea-packing data and SIF

Box 3.1. Paper II, short summary.
(Plet-Hansen *et al.*, 2018).

Sea-packing data from five vessels in 2015 and 2016 extracted from the SIF database was investigated. Because data from sea-packing is a new type of fisheries-dependent information it had to be validated against logbook and sales slips' data.
The validity of SIF data is not only vessel specific; it can also vary depending on the species. No clear factors were found that could explain these variations. For several vessels, SIF offer new and valid information. However, if using SIF as data input, one has to validate the quality of the data for each vessel and species for which the analysis is to be run.

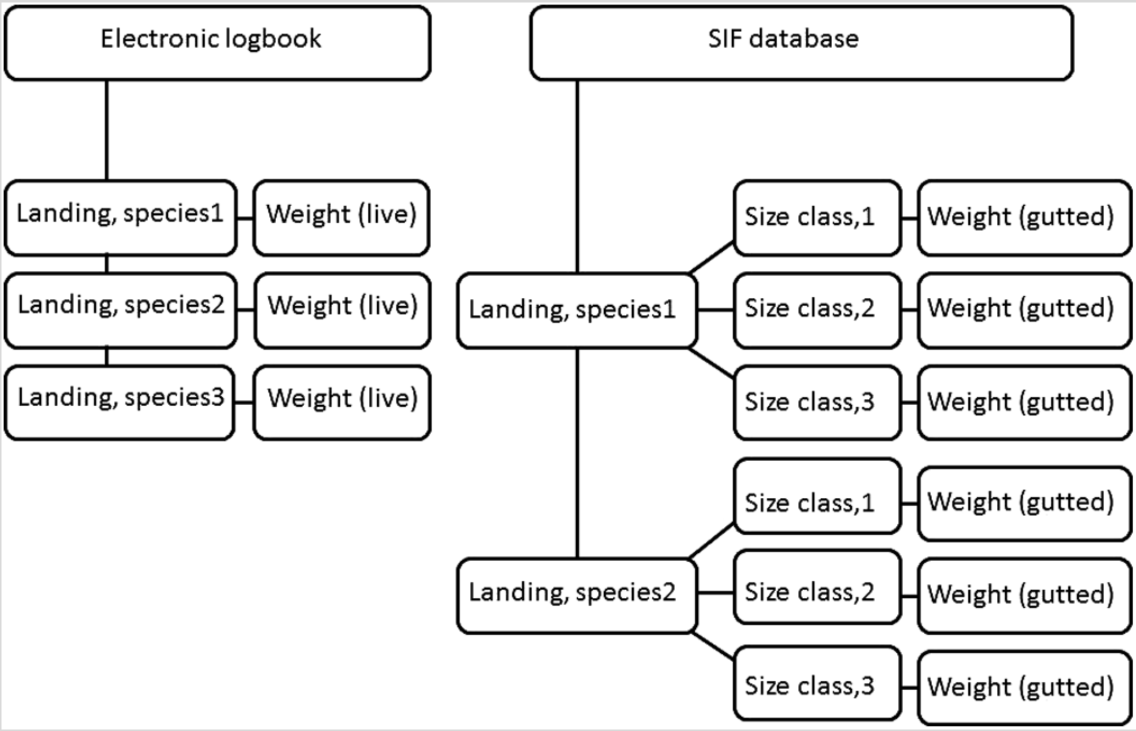

Figure 1 in Plet-Hansen et al., 2018. Conceptual figure of the difference between landings data available at haul level in the electronic logbook and the sea-packing data available in the SIF database.

Sea-packing involves the gutting, icing and packing landed fish in crates at-sea. The benefit of this is an increased quality of fish and a potential reduction in costs associated with the unloading of the landings in port (Frederiksen *et al.*, 2002; Frederiksen and Olsen, 1997). The on-board handling of fish is both manual and automatic, as the gutting and weighing of the fish is done automatically by grading machines, while the crew ensures species identification, size grading and packing in fish crates with ice. Principle machinery is presented in Fig. 4. Weighing is done in kilogram with dynamic scales at 2-digit precision. The grading machine software prints labels with species and size grade, which are added to the fish crates. By packing and labelling at-sea, vessels can bypass the fish collectors services (companies that split the landed fish in species, weight and quality, before packing the fish in boxes for the auction system), whereby the handling in port is reduced (Frederiksen *et al.*, 2002, 2001; Frederiksen and Olsen, 1997). The risk of mislabelling fish is minimised because the buyer can trace the batch of fish back to the vessel. Operational practices of sea-packing in Denmark thereby address traceability, accountability and trust considerations pointed to as focus points for future retail and policy requirements in fisheries (Probst, 2019; Schröder, 2008).

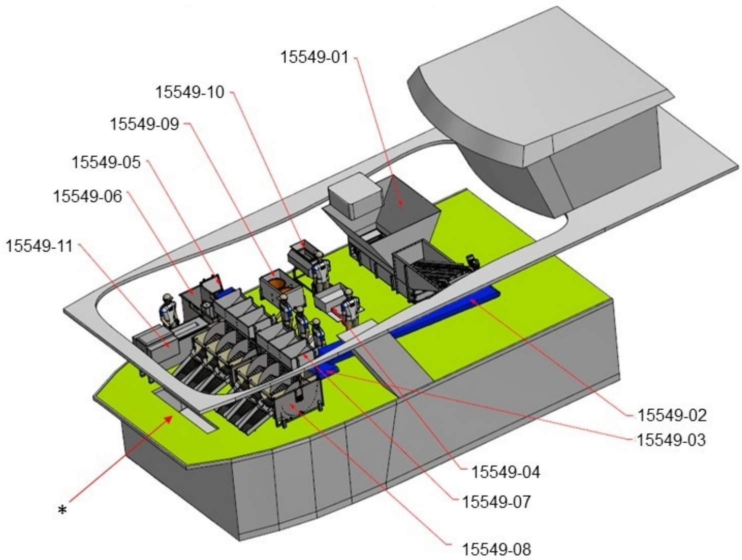

*Figure 4. Working area on-board a vessel equipped with marine whole fish grader, principal overview. Specific for sea-packing: 15549-11 (Gutting machinery), 15549-08 (Rotating flushers), * (hole for gutted and rinsed fish lower deck icing, packing and storing). Remaining numbers: 15549-01 (Catch entry), 15549-02 (lifting conveyor), 15549-03 (Sorting conveyor), 15549-04 (Nephrops packing area), 15549-05 (Discard chute), 15549-06 (lifting poundboard), 15549-07 (Overheadbinge for discards), 15549-09 (Dipping vessel for Nephrops), 15549-10 (Flusher for Nephrops). Adapted from Gemba, 2018.*

The “*Sporbarhed I Fiskerisektoren”* (SIF) system is essentially an add-on to sea-packing. Following stricter EU requirements in 2002 and 2009 for the traceability of food goods (EU, 2009, 2002; Schröder, 2008) – the same EU requirements leading to the development of VDEC and yellow catch information notes - SIF was developed as a collaboration between the Danish Fishermen's Association (DFPO), the Danish Fisheries Agency and the retail industry (Fig. 5).

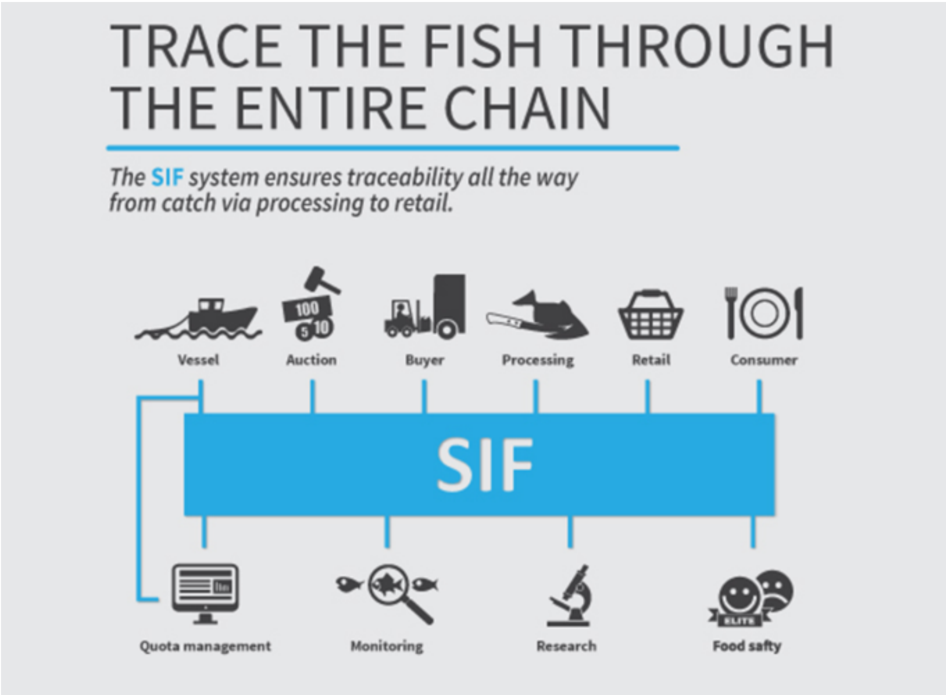

Figure 5. Conceptual overview of the possible interlink and applications of fishing data collected in SIF. Courtesy of SIF administration, http://www.sif-eu.dk/.

By linking the sea-packing data with the eLog, SIF contains information on haul times and position as well as the (gutted) weight grouped by species and commercial size class. In essence, SIF has the same information as the eLog but with commercial size class recorded as well, instead of merely species and with the gutted weight recorded instead of the live weight estimated. SIF also has yellow catch information note entries from a number of vessels but the data resolution remain the same for these as that of the yellow catch information notes.

Box 3.2. The making of Paper II.
(Plet-Hansen *et al.*, 2018).

Part of the PhD work was to investigate these traceability data collected by the Danish fishers. Sea-packing data and the data record system "Sporbarhed I Fiskerisektoren" (SIF) system was identified for this purpose. Based on discussions with colleagues at ICES conferences and working groups, the possibility to access such data is to my knowledge unique to Denmark. The complete data record for all Danish vessels listed in SIF is hosted by the company Lyngsoe Systems A/S, located in Aars, Denmark (Lyngsoe Systems, 2019). SIF have its own website with its own administrative operation (Pedersen, 2016). In order to access the data, consent had to be acquired from the individual vessel owners. Online searches and contact to fishers was used to find vessels likely part of the SIF system. Vessel owners were contacted by phone to ask for permission to access their SIF data and when vessel owners accepted, an email confirmation was sent as well. This written consent was then sent to the administrator of the SIF web access point, who then allowed for access to the given vessels' SIF entries. As no export function exists, entries had to be manually exported from the SIF website. To speed up this process, a web scraper was developed in Python 3.7.2 and run via R version 3.5.1. From the first SIF entry in 2013 to 2017, data from a total of 12,741 hauls have currently been extracted from eight vessels, all of which are demersal trawlers.

Because data from sea-packing is a new type of fisheries-dependent information it had to be validated. In terms of landings information, validation analyses were performed by comparing SIF with the merged information from logbooks and sales slips in the Danish Fisheries Analyses Database (DFAD) to estimate the agreement between these data sources. A linear model was used for this as the agreement should be 1 in the perfect world. Additionally, an analysis of covariance (ANCOVA) was run to test the effect of year, vessel and size class on any discrepancy between SIF and DFAD. To test for potential bias occurring if only certain size classes was recorded in SIF, a Wilcoxon rank-sum test as well as visual inspection was used. For haul information, SIF data originate from the eLog. As such, the SIF has the same validity as DFAD. However, as it was possible to obtain EM GPS sensor data for two SIF vessels, an estimate of the haul information validity could be made. This was done visually in a vector-based approach by plotting EM fishing activity data as points and SIF haul start and stop positions as lines. The mean latitude and longitude for the vessels in two years was analysed using Wilcoxon rank-sum test. Based on subsequent talks with fishers, it is clear that many factors influence the use of SIF and on-board grading machines. These can be both fishery and vessel specific, such as target species and market prices, but they can also be haul specific and based on empirical knowledge or expectations. A good example is plaice and monkfish landings for Vessel A in Paper II which target plaice and cod in the North Sea. The vessel owner explained that if a haul contain large quantities of plaice, the crew is instructed to not sea-pack plaice for the haul because of the risk of mislabelling due to tiredness. That is, the expected profit of sea-packing is deemed lower than the expected risk and associated cost of having to re-label crates. For monkfish, the vessel owner explained that it is his experience that monkfish shrink on ice when sea-packed and therefore the price is better by not sea-packing. This is despite the fact that monkfish is one of the species which is most likely to be sea-packed for the other vessels in the study. It is therefore very vessel specific how sea-packing and SIF is used and while some vessels clearly use the SIF system in a manner that do add knowledge not already accessible in the eLog and sales slips, others do not.

3.7 Electronic monitoring with video

Box 3.3. Paper III, short summary.
(Plet-Hansen *et al.*, 2019).

The reliability of electronic monitoring (EM) has been increased by technical developments and simple practical countermeasures, such as tilting cameras to avoid water droplets or using both wide and square lenses to improve field of view. This underpins EM as a feasible Monitoring, Control, Surveillance (MCS) tool. While automated image analysis is presented as the main development that can lower EM costs, video audit times have already decreased by optimising video audit routines in the presented Danish EM trial. EM is not a silver bullet that by default is the optimal solution for compliance or data collection, but it is a cost-effective measure compared to the current alternatives like on-board observers or at-sea control.

Figure 1 in Plet-Hansen et al., 2019. Left: Example of image for video audit with the first version of the grid overlay. Grid scale set on this example was a 10 cm interval. Right: Example of image for video audit with the final grid overlay and measuring line integrated in the Black Box Analyzer. The image shows the measuring line on a monkfish (Lophius spp.) of 65.7 cm in length in a curved position. The scale set for this grid overlay was 5 cm interval.

Canada was the first country to test the use of electronic monitoring with video in 1999 (van Helmond *et al.*, *In Press*). Since then, the use of EM has increased worldwide either as a MCS tool on its own, or together with on-board observers (Gilman *et al.*, 2019; van Helmond *et al.*, *In Press*). Recent technological developments, both for the EM hardware (sturdiness and cost of equipment) as well as for the software and analysis tools (swifter and better tailored analysis tools and machine learning applications) make EM increasingly relevant as a tool to ensure well-managed fisheries (Bergsson *et al.*, 2017; Bergsson and Plet-Hansen, 2016; Bradley *et al.*, 2019; Catchpole *et al.*, 2018; Gilman *et al.*, 2019; Needle *et al.*, 2015). In essence, an EM system consists of a GPS tracker to record positional data and cameras on-board to record video footage of activities (Bradley *et al.*, 2019). To optimize video footage analysis, sensors are typically added to highlight when activities occur, e.g. image sensors (Evans and Molony, 2011) or sensors on the gear such as hydraulic and/or rotation sensors to identify setting and hauling of gear (Gilman *et al*., 2019; James *et al*., 2019; Kindt-Larsen *et al*., 2011, 2012; Ulrich *et al*., 2015). Video footage, positional and sensor data is stored on on-board data storage units which are manually exchanged with, empty storage units when vessels are in port or which transmit the stored data when vessels are within internet service (Bergsson and Plet-Hansen, 2016; McElderry, 2008; van Helmond *et al*., *In Press*.)(Fig. 6).

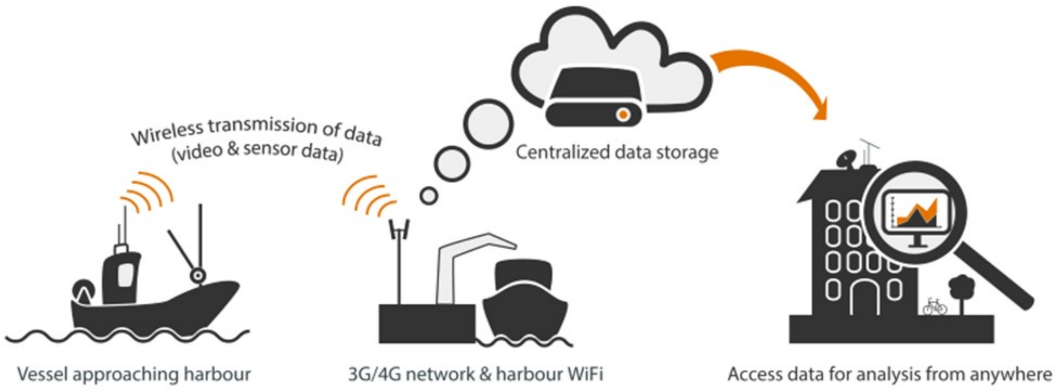

Figure 6. Basic overview of Electronic monitoring system with wireless data transmission capabilities. Courtesy of Anchor Lab K/S, H.C. Andersens Boulevard 37, 5. mf., DK-1553 Copenhagen V, Denmark, tel.: (+45) 4848 1553, e-mail: info@anchorlab.net.

At the time of writing, video audit by humans is still necessary (James *et al*., 2019; Needle *et al*., 2015; Plet-Hansen *et al*., 2019; van Helmond *et al*., 2017). However, the use of machine learning and automated image analysis to replace or reduce human supervision is believed to come into play soon (Bradley *et al*., 2019; Gilman *et al*., 2019; Huang *et al*., 2017; Hwang, 2017; McElderry *et al*., 2018; Scantrol Deep Vision AS, 2017; Wallace *et al*., 2015; Woodward, 2017). Exactly when such systems are fully developed is difficult to tell as work for this has been ongoing for years without yet reaching the goal (Bradley *et al*., 2019). Despite all these advancements, the uptake of EM has been slow, and is even put on hold in Europe where most EM trials have stopped after 2016 (van Helmond *et al*., *In Press*). The reasons for this are political and social and largely due to the resentment towards full monitoring in the fishing industry and the politically delicate matter of imposing full monitoring (Baker *et al*., 2013; Course, 2017; Mangi *et al*., 2015; Plet-Hansen *et al*., 2017). In 2019 however, this seems to change. The industry-perspective and the political interest in EM is re-emerging as it is seen as one of or the only suitable measure to ensure compliance with the landing obligation (Harvey, 2019a, 2019b; House of Lords European Union Committee, 2019; Ministry of Foreign Affairs of Denmark, 2018; STECF, 2018b). A working document for the Specific Control and Inspection Programmes as well as a proposal to amend the Control Regulation prepared by the European Commission both present EM as a tool to control the landing obligation and as a measure that should be implemented within the European fisheries control (EC, 2018a, 2018b).

Box 3.4. The making of Paper III.
(Plet-Hansen *et al.*, 2019).

Part of this PhD was to investigate the potential of electronic monitoring (EM) in the context of the landing obligation. All EM data used in this PhD thesis was collected as part of the Danish Cod Catch Quota Management trial (CCQM), which ran from 2010 to 2016 (both years included). Until 2014, the CCQM was a joint collaboration between DTU AQUA and the Danish Fisheries Agency, where the main use of the EM systems was to verify eLog entries in order to test Catch Quota Management (CQM) (Dalskov *et al.*, 2012; Plet-Hansen *et al.*, 2015; Ulrich *et al.*, 2015). In 2015-2016, the Danish Fisheries Agency solely ran the trial and the trial shifted its focus towards testing EM as a possible control measure for the landing obligation (Bergsson *et al.*, 2017; Bergsson and Plet-Hansen, 2016). Prior to this, discards were merely recorded by species and weight. After this change, length measurements became more accurate and were recorded as well. Vessel participation in the CCQM was voluntary with a quota uplift for cod and exemption from days-at-sea regulations given as incentive for participation. While the trial has been successful in terms of discard reduction and reliability of EM systems (Bergsson *et al.*, 2017; Bergsson and Plet-Hansen, 2016; Dalskov *et al.*, 2012; Ulrich *et al.*, 2015), the incentives and voluntary nature of the trial has led to critique regarding a selection bias for participating vessels (Msomphora and Aanesen, 2015).

An agreement was made with the Danish Fisheries Agency that allowed the processed data and a limited amount of vessel GPS sensor data from the CCQM to be used in this PhD. From the first EM data in 2010 to the last audited in early 2017, data from 7,690 hauls was available from 25 vessels. Of these, 2,589 hauls from 13 vessels had length measurements of audited discards. Previous studies had validated EM data from the CCQM (Bergsson and Plet-Hansen, 2016; Ulrich *et al.*, 2015). The focus of the paper III publication was instead on costs and reliability issues. Additionally, the discard length information in the post-2014 EM data allowed for analyses of discard composition by size and management area for vessels with a high monitoring coverage using frequency distribution and logistic regression.

4. Spatial analysis of fisheries data

Analyses of spatial data through Geographical Information Systems (GIS) cover a wide array of models, methods and applications. It is not possible to cover all methods in this thesis and not all methods are relevant to the topic (e.g. methods for topographical modelling like calculation of watershed, hillshade or viewshed) (Balstrøm *et al*., 2006). Rather, key concepts for the analysis of spatial data related to fisheries will be briefly presented, and the spatial analysis that are of particular relevance for this PhD will be highlighted.

4.1 Spatial autocorrelation

Autocorrelation is when nearby observations are more similar than observations that are further apart simply because the observations are closer to each other (Elith and Leathwick, 2009; Valavanis *et al*., 2008). Autocorrelation is not limited to spatial data and the principle tends to be more intuitive for temporal autocorrelation. An obvious example of this is e.g. weight through a person’s life, where if a person’s weight is measured regularly for 10 years, and the person gains 20 kg during this period, it is more likely that weight measurements taken close to each other in time are more related than those taken further apart. The same is likely for other parameters, for instance education level.

Spatial autocorrelation, although it is essentially the same as temporal autocorrelation, is more complex because time is one-dimensional, whereas space has at least two dimensions and topography and/or bathymetry adds further complexity to this (Bivand *et al*., 2008b; Kissling and Carl, 2008). As will be described in detail later, spatial autocorrelation is important to keep in mind when using fishery-dependent spatial data because the non-random distribution of fishing effort lead by default to spatial autocorrelation (Augustin *et al*., 2013; Kissling and Carl, 2008; Pennino *et al*., 2016; Poos *et al*., 2013; Sims *et al*., 2008).

4.2 The modifiable areal unit problem

The modifiable areal unit problem (MAUP) is an issue related to the aggregation of data into areas (for instance abundance, catch per area or discard ratios). The shape and scale of the aggregation (e.g. square grid or triangular grid of size A or size B) will affect the summary values because measurements will be set to refer to a specific area based on whether the measurements are associated to one or several of the areas (e.g. grid cells) (Dark and Bram, 2007). The issue is also referred to as grain choice or resolution for spatial data representation (Amoroso *et al*., 2018; Guisan *et al*., 2007). This issue of data grouping affecting the statistical outcome of quantitative analyses was first presented in 1934 (Gehlke and Biehl, 1934), but persists as a difficult issue, particularly relevant when spatial data analyses are used for recommendations on planning and management (Salmivaara *et al*., 2015). An example of the effect of MAUP in fisheries science is the recent controversy of how large a share of the world’s ocean is fished every year. Depending on the chosen grid size for spatial analysis, some authors estimated the annual footprint of fishing to be covering 55% of the world’s ocean (Kroodsma et al., 2018), while others estimated it to be as low as 4% (Amoroso et al., 2018).

Several solutions to minimize the MAUP exist, ranging from simply ignoring MAUP to not aggregating data at all, thereby analysing each individual observation in the investigation (Dark and Bram, 2007; Jelinski and Wu, 1996). It is however often useful and necessary to aggregate data to some extent, but scientists should not ignore this potential bias. As such, a reasonable approach to the MAUP is to acknowledge its existence and try to minimize its potential effect by setting areal units and aggregation levels in accordance with the quantity and variability of the input data (Salmivaara *et al*., 2015).

4.3 Presence-only, presence-absence or abundance data

Although there is overlap in modelling methods for presence-only compared to presence-absence and abundance models, presence-only data is inherently different from the two others. Presence-only data simply contain information of known occurrences (presences) for the investigated species with no information of absence (Elith and Leathwick, 2009; Valavanis *et al*., 2008). Presence-only data can simply be due to what data it was possible to collect at the time and some authors argue that presence-absence or abundance data would add more robustness to the modelling of species distribution (Elith and Leathwick, 2009). Please see section 4.4 and Supplementary material for more details on species distribution modelling. However, data may also purposely be limited to presence-only because some other authors argue that abundance and presence-absence data may introduce bias to certain analyses since the absence of a species at a site may reflect lack of equilibrium for the species or environment or simply reflect a false absence (Elith and Leathwick, 2009; Lobo *et al*., 2010). Lobo *et al*. 2010 identify three kinds of absences, i) contingent absence, ii) environmental absence and iii) methodological absence. Contingent absence describes when a species is absent in a seemingly environmentally friendly area due to local factors such as local extinction, biotic interactions or dispersal limitations (Lobo *et al*., 2010). Environmental absence is caused because of unfavourable conditions in an area. While both contingent and environmental absence are true absences, they reflect different processes and environmental interactions with the species' habitat. The last category, methodological absence, is caused by sampling bias, whereby the data collection method or data collection frequency may be unsuitable to ensure the validity of observed absences (Lobo *et al*., 2010). While this is not a unique issue for fisheries, there is no doubt that methodological absence is a factor to consider when modelling the distribution of fish species. Fishery-dependent data, such as on-board observers or landings data, are by nature biased and will not reflect true absence, as there is both a targeting effect and a gear selectivity effect which filter out some species actually present in the area (Kristensen *et al*., 2014; Verdoit *et al*., 2003). Fishery independent data, like survey data, are less biased but suffer from low sampling frequency, which can miss out on the occurrence of rare species (Bourdaud *et al*., 2017; Pennino *et al*., 2016; Verdoit *et al*., 2003).

Unlike absence data, presence and abundance data will by default be a true record (unless mislabelling has happened) (Elith and Leathwick, 2009). Yet, basic knowledge on data and on the data collection method to collect them is very important, especially regarding abundance data as the recorded amount may be skewed due to the same factors as false absence (whereas the mere record of the presence as a categorical record is not affected by the amount) (Elith and Leathwick, 2009; Potts and Elith, 2006).

Commercial catch information is therefore argued by some authors to be more useful for analysis of fish above any specified minimum landing size (Valavanis *et al*., 2008). However, methods that can account for methodological sampling bias are developed because of the opportunities for added data if preferential sampling can be accounted for in the spatial modelling (Conn *et al*. 2017; Pennino *et al*. 2019). The scientific use of fisheries dependent data like EM and SIF is therefore possible if using appropriate methods and keeping in mind the limitations and underlying assumptions caused by the specificities of these data sources.

4.4 Methods for the spatial analysis of fisheries data

Box 4.1. Book chapter I, short summary.
(Reid *et al*., 2019).

Using electronic monitoring (EM) data from a Danish EM trial the spatial discard distribution of cod, hake, saithe, whiting and haddock was presented for the North Sea and Skagerrak.

Using sales slips' records of prices per kg for commercial species and size classes together with the SIF sea-packing data and the EM data, raster maps of vessels' per haul value in euros with discard hotspots added as points based on a given discard threshold were generated.

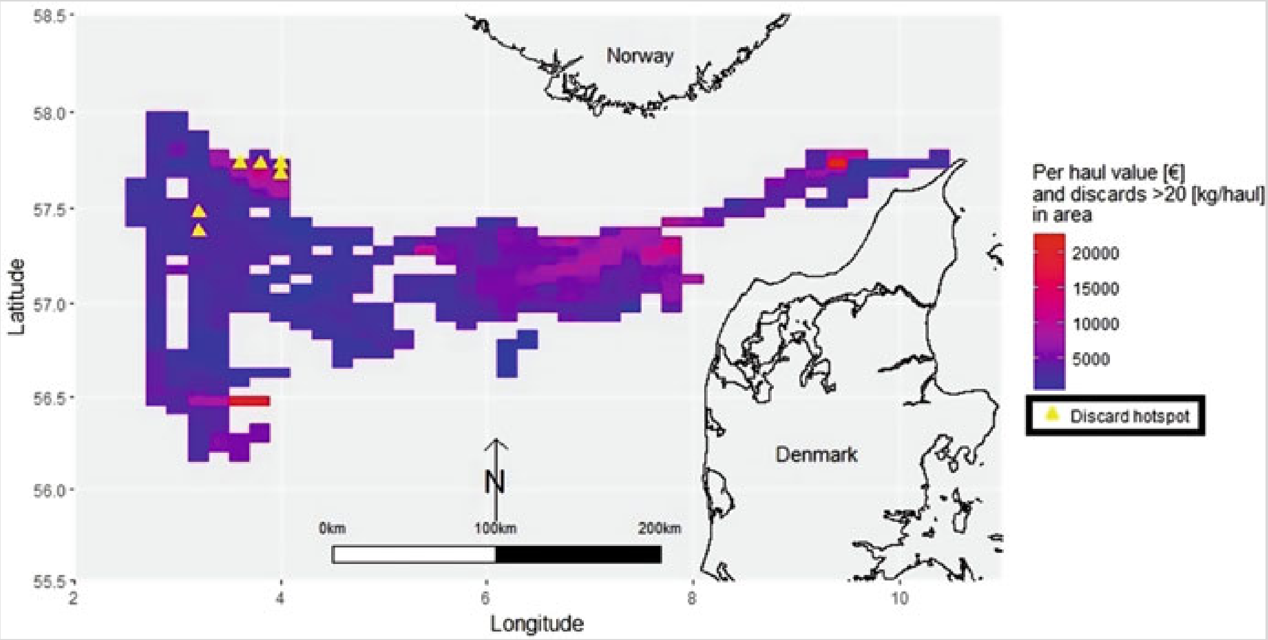

Figure 13.12 in Reid et al., 2019. Gridded map of the landing value per haul for a single Danish trawler. The red colour represents the greatest value per haul. The yellow triangles represent the areas of high discard volumes. The discard hotspot areas often coincide with high value hauls but importantly, there are also other high value areas without such high discard levels.

As for other topics where spatial analysis is used, an array of approaches exist for the spatial analysis of fisheries (Bastardie *et al*., 2010; Bourdaud *et al*., 2018; Lewison *et al*., 2009; Pennino *et al*., 2019, 2016; Pointin *et al*., 2018; Sims *et al*., 2008). First, the objective of the analysis must be clearly specified: Is the spatial analysis directed at the fisheries or at the fish (or other marine species)? The data needs and the suitable model approach will depend on this because of the differences between fishery-dependent data and fishery-independent data. Fishery-dependent data is collected with the specific setup applying to the given fishery in which the data collection takes places. That means that already at the collection stage, fishery-dependent data have been through a temporal, spatial and technical filtering (Fauconnet and Rochet, 2016; Feekings *et al*., 2012; Madsen and Valentinsson, 2010; Smith, 2000). The reason for this is that fishers use gears which have a certain selectivity (Fauconnet and Rochet, 2016) and distribute their fishing effort based on the goal of optimizing their catch and profitability (Smith, 2000). Several criteria influence this tactical choice, for example expected value, remaining quota, empirical knowledge and tradition, cost of steaming and expected weather (Bockstael and Opaluch, 1983; Feekings *et al*., 2012; Gillis and Frank, 2001; Monroy *et al*., 2010; Ulrich and Andersen, 2004). Combined, these factors lead to a non-random spatial distribution of the fishing effort within a given management area as fishers target specific fishing grounds (Augustin *et al*., 2013; Pennino *et al*., 2016; Poos *et al*., 2013; Sims *et al*., 2008). In addition to the non-random distribution due to fisheries tactics and regulations, the use of fisheries data for spatial analysis is also challenged by characteristics like a tendency for patchiness or clustering due to interplay between oceanographic features and species behaviour (Ciannelli *et al*., 2008; Mann and Lazier, 1991).

Non-random distribution of data points is not limited to fisheries data, and approaches to account for and incorporate non-random data collection cover methods specifically addressing fisheries' data but also methods previously used within other areas of research, for instance image analysis or mapping of disease outbreaks (Besag *et al*., 1991; Pointin *et al*., 2018; Sims *et al*., 2008). Methods for analysis and visualisation include:

Point pattern analysis:

Georeferencing fishing activity to a point, for instance midpoint of haul distance or setting location of a gillnet, and then treating this location as the sample station for the catch information (Lewison *et al*., 2009; Sims *et al*., 2008).

Area pattern analysis:

Summarization of points or transect samples in predefined grid cells (e.g. ICES squares). Sample values taken within the area are summarized as for instance total number or weight, mean number or weight or ratios like discard ratio or rates like Catch Per Unit of Effort (CPUE) to name some (Bastardie *et al*., 2010; Lewison *et al*., 2009; Sims *et al*., 2008).

Nested grids:

Nested grids is an area pattern analysis. However, the setting of grid cell size is here different from other area pattern analyses. Instead of predefining a fixed size, the grid cells have different size depending on the densities of observations. This makes it possible to decrease the spatial resolution in areas where sampling is abundant while still representing areas with few observations and highlighting that data availability is a limiting factor in these low sampling areas. To achieve this, large grid cells are first set at a very coarse level and then divided in half again and again until a predefined minimum number of observations or predefined minimum grid cell size is reached. The method was introduced to deal with the non-random data sampling in fisheries-dependent data (Gerritsen *et al*., 2013; Pointin *et al*., 2018).

Species distribution modelling:

The term species distribution models (SDMs) cover a wide variety of models, which aim at linking field observations to ecological and environmental factors and/or at making predictions on the distribution of species (Collins and McIntyre, 2015; Guisan and Thuiller, 2005; Torres *et al*., 2015). Input data can be presence-only, presence-absence or abundance (Elith and Leathwick, 2009; Guisan and Thuiller, 2005; Valavanis *et al*., 2008) and originate from specific sampling or from opportunistic data sources such as commercial data or citizen science (Guisan and Thuiller, 2005; Hochachka *et al*., 2012; Poos *et al*., 2013). A distinction should be made between the realized and potential distribution of a species. The potential distribution is where a species could live based on the environmental factors while the realized distribution is where the species actually live (Torres *et al*., 2015). Modelling the realized distribution uses interpolation between observations within a relatively restricted area to predict on species presence for the area, whereas modelling the fundamental or potential distribution needs to extrapolate observations to areas outside of the sampling area. Although environmental factors are taken into account, such extrapolation is not as robust as when predicting the realized distribution (Guisan and Thuiller, 2005; Torres *et al*., 2015). More details to different model approaches in SDMs are given in the Supplementary material.

4.5 Near real-time spatial management

The United States' Alaskan eastern Bering Sea Pollock fishery is an example where spatial management of effort allocation and bycatch cap regulations is implemented (Branch *et al*., 2006, Little *et al*., 2015; S. Martell, Sea State Inc., personal communication). The data collection and transmission systems is advanced, collecting VMS and observer data for positional and catch information and using this for spatial management within no more than 24 hours (Little *et al*., 2015; S. Martell, Sea State Inc., personal communication). Yet, the actual spatial analysis and management is quite simple. Visual inspection of geographic location and timing of hauls together with gradient colouring based on bycatch amount or bycatch ratio is used to distribute rolling hotspots, which are temporary closed areas. While clear spatial patterns in the appearance of bycatch species in the collected data are often observed, sometimes the patterns are not as clear. For instance if spatial avoidance of one bycatch species might interfere with avoidance of another bycatch species, e.g. avoidance of sablefish (*Anoplopoma fimbria*) interfere with avoidance of chinook salmon (*Oncorhynchus tshawytscha*) (S. Martell, Sea State Inc., personal communication). In such instances, the approach is to setup best estimated rolling hotspots and rely on the swift data collection to assess whether these hotspots needs to be adjusted (S. Martell, Sea State Inc., personal communication).

Box 4.2. The making of book chapter I.
(Reid *et al*., 2019).

As part of the Horizon 2020 project "DiscardLess", this PhD contributed to the objective of developing Decision Support Tools for fishers to optimise their spatial selectivity as well as finding case studies on the application of state-of-the-art systems to address spatial selectivity. Acknowledging that fishers in essence do not fish for fish but for money, another approach than viewing landings and discards and weights or ratios was explored. In a mixed-demersal fishery with the possibility for quota lease and quota swapping as the Danish ITQ-system, spatial selectivity might be better tailored to the industry if the monetary importance rather than weight or species specific information is visualized.
This approach turned out to be surprisingly close to what some sea-packing vessels already do. When presenting these ideas to fishers, the response from some was that they already use an interface with SIF to see their previous haul tracks and its associated catch (retained catch only) based on criteria they decide. Although this does not include discards, it does show that some Danish fishers use spatial selectivity in ways, which are relatively close to that of the Sea State Inc. system used in the United States' Alaskan eastern Bering Sea pollock fishery described above.

5. Ongoing studies and next developments of this PhD work

A joint publication between the Marine Institute in Ireland and DTU Aqua is in draft. The publication extend on the concept of trade-off between discard hotspots and haul value presented in Box 4.1 with in-depth analysis of historic discards and associated landings value for the Celtic Sea and the North Sea.

Beside this, the work of coupling SIF and EM data is ongoing. The merging of the two datasets has been performed successfully for six vessels, but the initial examinations have not revealed obvious patterns, which could have been included in the scope of this PhD, and more work is needed. At the time of writing, preliminary results are already available for two analyses for SIF and EM data, which are briefly presented here.

5.1 Linkage between commercial size landings and discards at the haul level

An initial investigation to examine the possible link between the size of landings and discards of cod, haddock, saithe, whiting and hake at the haul level has not led to clear results. The underlying idea was that one would expect fish aggregations to follow a normal distribution in size and not knife-edged management size classes. As such, one could expect that hauls with a large share of small commercial size classes would also have contained a large share of the smallest sized individuals (below MCRS, hence discarded) than hauls with a larger share of bigger commercial size classes. However, initial analyses testing the accuracy of linear modelling to predict discard occurrence based on occurrence of landed size classes, as well as the use of an artificial neural network to predict a pattern in the occurrence of discards based on landed size classes have failed to predict discards. While this may at first seem counter-intuitive, in fact a number of reasons may explain this. Because the size class data is derived from a fishery-dependent source, gear selectivity mean that undersized fish should be less likely to be retained in the trawl (Madsen *et al.*, 2010; Valentinsson *et al.*, 2019). Adding to this, the investigated vessels were managed with CQM for cod catches while having EM, meaning the incentive for avoidance of undersized cod catches was particular high. The MCRS for cod in the North Sea and Skagerrak was at the same length or higher than that of haddock, hake, saithe and whiting (EU, 1998; Fiskeristyrelsen, 2019). It is therefore possible that selectivity directed at avoiding undersized cod would have a positive knock-on effect on undersize catches of haddock, hake, saithe and whiting. Indeed, all vessels from which EM discard data could be derived and coupled to SIF landings data, used >120 mm mesh sizes in their trawl. Avoidance tactics employed by the vessels to increase their spatial selectivity for cod may also have relayed to other gadoid species that tend to be caught together with cod such as haddock or whiting (Kraak *et al.*, 2013; Ulrich *et al.*, 2011). Indeed the number and amount of undersized discards was actually quite low for the investigated vessels. Of 201 hauls with SIF and EM data for cod, 137 (68.2%) had zero discards of undersized cod recorded and 24 hauls had less than 0.3 kg of discards recorded. This left only 40 hauls (19.9%) with more than one undersized cod discarded. The low number of observations may therefore also have influenced the analyses. Additional SIF data from vessels with available EM data has not been possible to acquire at the time of writing and this work is therefore currently on hold.

5.2 The added value of haul level size information

"Essentially, all models are wrong, but some are useful". The famous quote from George E. P. Box (Box, 1979) capture the duality of modelling. To estimate whether a model is useful, model validation is important. Methods for this can be to compare the predicted model output based on model training data with observed data that is independent of the model training data (Araújo *et al.*, 2005; Pearce and Ferrier, 2000) or cross-validation when independent data is not available (Stone, 1974). Model performance can be evaluated by its ability to discriminate, that is its ability to predict presence and absence sites, which can be tested using true skill statistic or area under the curve (AUC) (Allouche *et al*., 2006; Manel *et al*., 2001). Another performance approach is to evaluate the model reliability, that is, to estimate the agreement between predicted presences and observed proportions, using measures such as mean absolute prediction error or root mean squared error (Liu *et al*., 2011).

Multicomponent metrics is another approach, which has been proposed within the field of hydrology as a mean to create cross-sectional model validation and lower the effect of pre-analyses selected validation metrics (Gupta *et al*., 2012; Krause *et al*., 2005). An example of such a metric is the SPAtial EFficiency metric (SPAEF) which use Pearson's correlation coefficient, coefficient of variation and histogram overlap to produce a single metric (SPAEF) as well as presenting the three input components, all of which having 1 as the value representing a perfect fit (Koch *et al*., 2018).

In this ongoing analysis, SIF data is used to test the difference in spatial allocation of size landings depending on whether haul or trip level information of size is available. Additionally, the influence of grid cell size is investigated. The analysis has two purposes:

1) Estimating the gain of having size information at the haul level, as in SIF, compared to size information at the trip level, as in the currently used Danish Fisheries Analyses Database (DFAD).

2) Estimating the MAUP effect, described in section 4.2, of different grid cell sizes.

Preliminary results using the SPAEF metric (Koch *et al*., 2018) indicate that the additional gain of size information at the haul level not only is species specific but indeed also depend on the chosen grid cell size (Fig. 7).

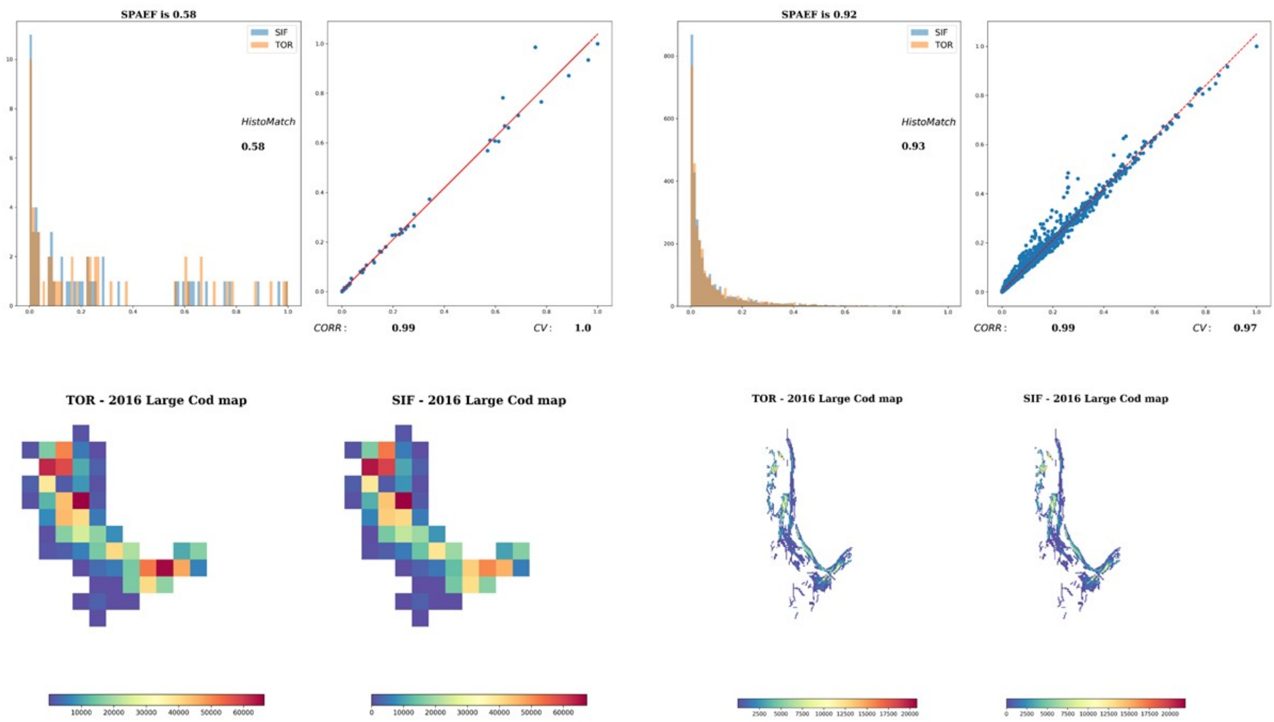

Figure 7. SPAEF output for large sized cod (above 2 kg) in 2016, comparing trip-level information (TOR) to haul-level information (SIF) depending on grid resolution as ICES grid (left) or as grid size equal to 0.05 ^{0} by 0.05 ^{0} (right).

The SPAEF coefficient is 0.58 for ICES square grids and 0.92 for 0.05^{0} by 0.05^{0} grid cells. This mean that for large cod (> 2kg) grid cells with a smaller size have more agreement between trip-level and haul-level information (Fig. 7).
Extending this to other species as well as smaller sizes, the overall trend is the same (Fig. 8). Figure 8 shows that except for whiting, monkfish and small wolffish, all investigated species and size-groups show a trend towards coefficients close to 1 between haul-level information and trip-level information. Especially the histogram overlap drives this, which is likely related to the number of hauls passing through a given grid cell. This suggests that information of size at the haul level can add knowledge when fishing effort data has a low resolution, and conversely that trustworthy high-resolution data on fishing effort lower the spatial bias from redistributing trip-level size information to the haul level.

The publication of these results is planned together with co-authors Clara Ulrich, IFREMER and François Bastardie, DTU AQUA. The manuscript for this is in its first draft and the ongoing work is expected to allow for submission in early 2020.

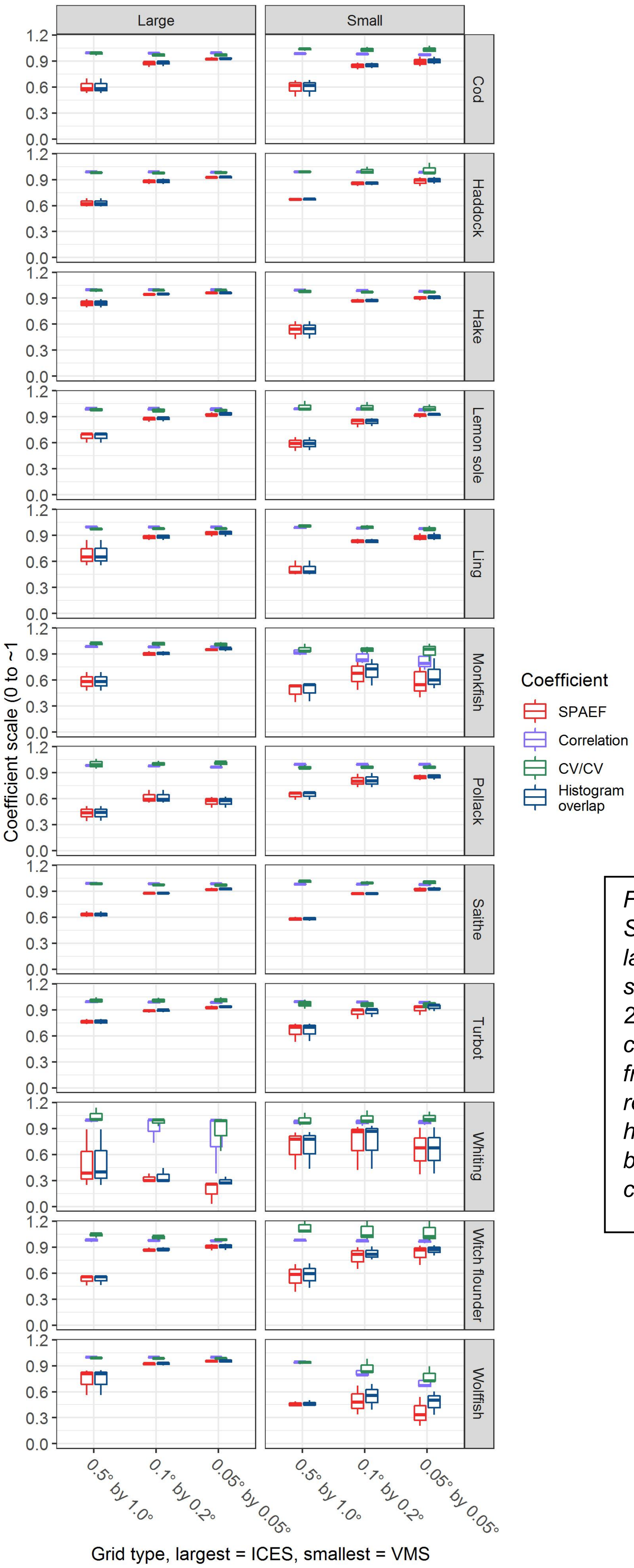

Figure 8. Boxplot of outcomes for SPAEF and its three coefficients for the large and small size group of the 12 species by three grid cell sizes in 2015-2017. Correlation is Pearson's correlation coefficient, CV/CV is the fraction of the coefficient of variation representing spatial variability and the histogram overlap is the intersection between histogram for haul-level compared to trip-level information level.

6. Conclusion

The landing obligation has challenged fishers, fisheries managers and fisheries scientists. New methods to support fishers in adjusting their fishery and adapt to the new regulation are being developed and techniques and systems developed prior to the landing obligation now help in the transition to the new management regime too. Systems like sea-packing and electronic monitoring have a dual applicability within the context of the landing obligation. On the one hand, these systems can assist fishers with additional information to fill in their logbooks, adjust their fishery and increase their selectivity. This is an area where more can be done to ensure that fishers can utilize their own catch and effort data directly to optimize of their activities. On the other hand, traceability systems and especially electronic monitoring can be used to enforce compliance with the landing obligation. While the technical and practical limitations to this are minor – similar management is enforced with electronic monitoring in other parts of the world – the social aspect is important to remember. Electronic monitoring and traceability can function as a tool to ensure compliance but if forced upon the fishery in a top-down approach, there is a risk that the system will be perceived by fishers as a control tool rather than as a tool to assist the industry in compliance assurance. Creating the right incentives is key and the uptake of the SIF traceability system among fishers in Denmark is a good example of how regulations create innovative methods to increase the profitability of the fisheries. Further studies utilizing this opportunistic data to shed light on the effect of data detail level for fisheries management are not only expected, but also ongoing. Bringing this work into the ICES context through ICES Working Group on Technology Integration for Fishery-Dependent Data (ICES, 2019b) and future publications is the next stage for my work on SIF and EM.

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Remote electronic monitoring and the landing obligation – some insights into fishers' and fishery inspectors' opinions

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ABSTRACT

The European fisheries management is currently undergoing a fundamental change in the handling of catches of commercial fisheries with the implementation of the 2013 Common Fisheries Policy. One of the main objectives of the policy is to end the practice of discarding in the EU by 2019. However, for such changes to be successful, it is vital to ensure stakeholders acceptance, and it is prudent to consider possible means to verify compliance with the new regulation. Remote Electronic Monitoring (REM) with Closed-Circuit Television (CCTV) has been tested in a variety of fisheries worldwide for different purposes and is currently considered as one possible tool to ensure compliance with a European ban on discards.

This study focuses on Danish fishery inspectors and on fishers with REM experience, whose opinions are less well known. Their views on the landing obligation and on the use of REM were investigated using interviews and questionnaires, and contrasted to some fishers without REM experience. 80% of fishery inspectors and 58% of REM-experienced fishers expressed positive views on REM. 9 out of 10 interviewed fishers without REM experience were against REM. Participation in a REM trial has not led to antipathy towards REM. Fishery inspectors saw on-board observers, at-sea control and REM as the three best solutions to control the landing obligation but shared the general belief that the landing obligation cannot be enforced properly and will be difficult for fishers to comply with. The strengths and weaknesses of REM in this context are discussed.

1. Introduction

The pressure for a change in fishing practices in the European Union (EU) increased throughout the 2000s, not least due to public demand like the *Fish Fight* campaign that demanded the end of discarding in the EU [1–4]. Discards are the part of the catch that is returned to the sea [5]. The public and environmental NGOs perceive discarding as unsustainable, unethical and a waste of resources, which has led to attempts to limit or end the practice [4,6–9]. Measures for this include increased gear selectivity, effort restrictions, quota limitations, temporal and spatial restrictions, transferability of quotas and discard bans [3,10,11]. Discard bans have been in place in Iceland since 1977, in Norway since 1983 and at the Faroe Islands since 1994 [11,12]. With the entry into force of the landing obligation of the 2013 Common Fisheries Policy (CFP) a discard ban is now also being implemented in the EU [13]. Banning discards is meant to ensure that total catches do not exceed the threshold defined by the regulatory framework (e.g. Maximum Sustainable Yield, MSY). Compliance with the landing obligation therefore requires a Catch Quota Management scheme (CQM) that aims at managing both wanted and unwanted catches. Documentation of all catches is thus required to verify CQM, a concept referred to as Fully Documented Fisheries (FDF) [4,14,15]. Measures to conduct FDF include self-sampling, reference fleets, on-board observers and Remote Electronic Monitoring (REM) with Closed-Circuit Television (CCTV) [16]. The use of REM with CCTV, henceforth referred to as REM in this paper, as a tool to obtain FDF has been tested in a number of countries, including Canada, the US, Australia, New Zealand, Denmark, the UK, the Netherlands and Germany [14,15,17–31]. Ongoing technological developments are taking place to increase the reliability, the cost-efficiency and the scientific added-value of the data collected by REM [23,32]. The primary reservation against REM has however not been on data validity but on the ethical dilemma as to whether the surveillance level imposed by such a measure is acceptable [3,16,33]. A study among UK

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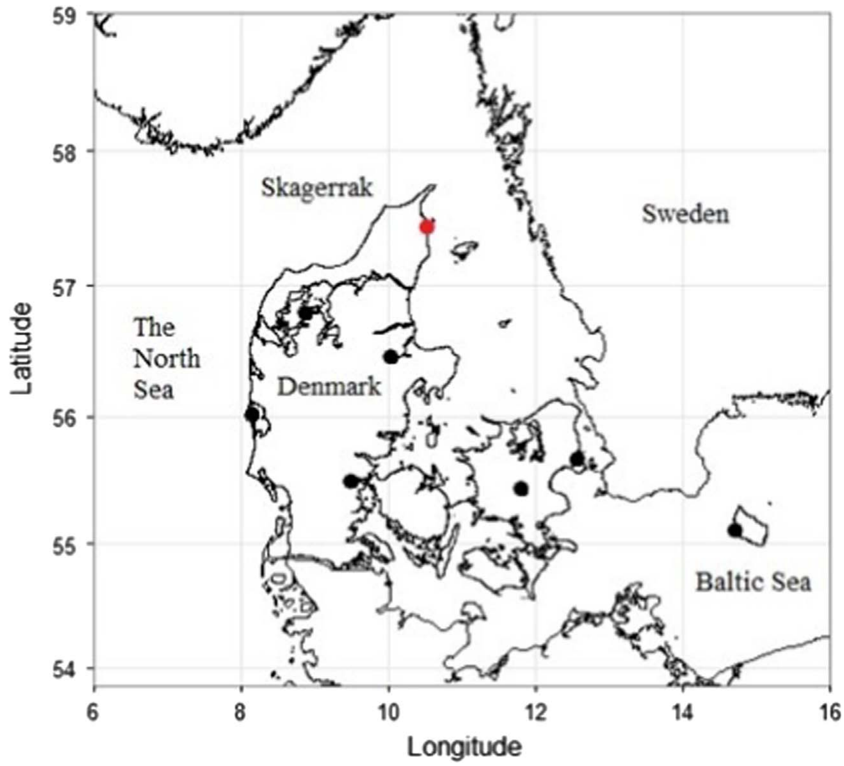

Fig. 1. Permanently manned fisheries control departments in Denmark. Black dots represent departments from where responses to the questionnaire were obtained, seven in total. Red dots represent departments where no responses to the questionnaire were obtained, one in total.

fishers showed that REM was seen as an intrusion and that fishers had concerns on whether video footage could be used to discredit the fisheries [16]. The authors also investigated which incentives could mitigate the perceived nuisance and encourage participation in FDF, with direct payment and additional quota scoring highest [16]. Much less known are the views among another primary group of REM users, the fishery inspectors in charge of enforcing the regulations imposed on the fisheries. The nature of their work and their day-to-day interactions with fishers provide fishery inspectors with experience and detailed understanding of regulations and of practical issues in the fisheries, but little attempt has been made so far to collect their knowledge and integrate it into the design of the fishery policy. Accordingly, this study investigates the opinions of Danish fishery inspectors' on the use of REM as a measure for control, monitoring and surveillance (MCS) and on their expectations for the landing obligation, in order to assess whether coercive measures are likely to be needed to ensure compliance with the landing obligation. A similar investigation among some Danish fishers is also conducted, including both fishers with and without REM experience, in order to contrast the results. The main driver for fishers is to ensure profits through the harvest of fish stocks whereas fishery inspectors' main objective is to enforce fishery regulations: Hence, it is expected that the perception on the meaningfulness and the viability of different regulations as well as on the practical obstacles imposed by these regulations may vary between these two groups of stakeholders. This article therefore aims at highlighting specific areas of convergence or divergence of perceptions between fishery inspectors and fishers.

2. Material and methods

2.1. Questionnaires for fishery inspectors

The Danish fisheries control is organised as part of the Danish AgriFish Agency under the Ministry of Environment and Food of Denmark. The fisheries control is organised with the central office placed in the capital, seven departments with a permanent staff and three control vessels [34,35]. The collaborators at the Danish fisheries control stated that they preferred a questionnaire to semi-structured interviews and believed that a higher proportion of responses would be obtained if the fishery inspectors received and responded to the questionnaire by email rather than if they were contacted in person or by telephone. A questionnaire covering 16 questions and intended to take approximately 10 min to complete was therefore developed. The majority of the questions were open-ended questions, except for questions relating to the ranking of MCS measures and positive/negative effects on the marine environment and fisheries, which were close-ended, though with possibility for a follow-up explanation. Prior to distribution, the questionnaire was tested and revised with a Senior Fisheries Officer from the Danish AgriFish Agency experienced with the use of REM in the fisheries control. A Chief Officer distributed the questionnaire by email to all sections in the Danish fisheries control. The Danish fisheries control head office in Copenhagen did not actively encourage fishery inspectors to respond to the questionnaire but knew of it and permitted the survey. Respondents returned the filled questionnaire by email to the Chief Officer who collected and forwarded the questionnaires. Respondents were thereby anonymous to the author of this article but not to the Chief Officer. On two occasions, the Chief Officer sent reminders to departments from where no responses had been received after three months. In total, these reminders led to four additional respondents. Based on the diverse answers from the respondents (see Section 2.2) this central collection is not expected to have influenced the answers from the respondents.

2.2. Fishery inspectors' representation

The total number of relevant fishery inspectors in Denmark was 95 at the time of writing. 30 fishery inspectors filled in and returned the questionnaire, corresponding to 31.6% of Danish fishery inspectors. Respondents came from the central office in Copenhagen, from six out of seven regional departments and from two out of three control vessels

Table 1
Diversity in geography and job title among responding fishery inspectors depending on REM-experience.

	REM-experienced fishery inspectors, n=21	Non-REM-experienced fishery inspectors, n=9
Department	Control vessel "Vestkysten" (n=6) Control vessel "Havørnen" (n=1) Fredericia (n=4) Nykøbing Mors (n=4) Hvide Sande (n=2) Rønne (n= 1) Copenhagen (n=1) Department not specified (n=2)	Control vessel "Vestkysten" (n=2) Control vessel "Havørnen" (n=1) Fredericia (n=1) Ringsted (n=1) Hvide Sande (n=1) Randers (n=1) Control vessel, unspecified (n=1) Department not specified (n=1)
Title	Fishery inspector (n=10) Vice fishery inspector (n=1) Senior fisheries officer (n=1) Master mariner (n= 3) Chief Officer (n=3) First mate (n=2) Title not specified (n=1)	Fishery inspector (n=3) Senior fisheries officer (n=1) Master mariner (n= 2) First mate (n=2) Title not specified (n=1)
Type of REM experience	At-sea control on a vessel with REM (n=9) Changed REM hard drives on vessels (n=8) Reviewed video footage (n=3) Drafted terms for REM trials (n=1)	None (n=9)

(Fig. 1).

Out of the 30 respondents, 21 had experience with REM (Table 1). Of these 21, nine had encountered REM while undertaking an inspection of a vessel, implying that these fishery inspectors have seen but not engaged in the use of a REM system. Eight of the 21 had changed hard drives on vessels participating in a trial using REM. Three of the 21 had viewed some of the video footage recorded by a REM system. One of the 21 had participated in the drafting and implementation of regulations in connection with the usage of REM. Various trials on REM have been conducted in Denmark since 2008 [14,15,28,29] and some were still in operation at the time of writing. There has thus been ample time for fishery inspectors to encounter a vessel with REM. It is therefore not seen as a bias that 70% of responding fishery inspectors has encountered REM in some way.

2.3. Interviews with fishers

A total of 22 interviews with fishers were conducted between 7 September and 9 November 2015 based on questions similar to those in the questionnaire distributed to the fishery inspectors but including questions related to practical fishing issues and to specific experiences with REM trials when relevant. Questions related to opinions on the effects of the landing obligation and REM was the same for fishers as for fishery inspectors. Of the 22 interviews, 14 were conducted at the 24th International Fisheries Exhibition, *DanFish,* in Aalborg, Denmark from 7 to 9 September 2015. During the exhibition, 43 fishers were approached with 14 willing to be interviewed. This exhibition was chosen as the main place for interviewing fishers because it provided an opportunity to contact a large number of fishers within a short time frame. Additionally, it was expected that fishers attending the exhibition would be more likely to take the time to be interviewed without prior arrangements because they would not be influenced by external factors like good or bad fishing weather. However, collecting interview data at the *DanFish* exhibition limited the sampling frame to fishers who were attending the exhibition, including only a small number of fishers with REM experience. Therefore, eight additional interviews were conducted by telephone from 14 October to 9 November 2015. Fishers interviewed by telephone had given their contact information and declared their willingness to participate in a telephone interview during a local meeting on the use of REM held on 18 August 2015. Present at the meeting were representatives from the Danish AgriFish Agency, DTU Aqua, the Danish Fishermen's Association and local fishers – mainly skippers - in Hanstholm, Denmark. This prearranged possibility for future interviews allowed for an extension of the data gathered from fishers' interviews, including more responses from REM-experienced fishers. Incidentally, it cannot be excluded that there is a bias in the data arising from differences between face-to-face and telephone interviews, even though the questions were the same. Interview time ranged between 30 and 45 min for both interviews conducted face-to-face or by telephone. Difference in length of interviews mainly depended on the number and length of explanations made by fishers to clarify their responses.

2.4. Fishers' representation

A total of 22 fishers were interviewed. Of these, 12 had experience with REM by being participants in Danish REM trials, and 10 had no experience with REM (Table 2).

By coincidence, the fishers without REM experience interviewed at the exhibition represented a more diverse part of the Danish fishing industry in terms of gear type, target species and area than the interviewed REM-experienced fishers, who were all operating demersal trawlers in the North Sea and Skagerrak. The largest and longest running Danish trial on REM is the Cod Catch Quota Management trial which started in 2010 [14,15]. Although some Danish seiners and gillnetters have participated in this trial, the majority of vessels have been trawlers [14]. The incentives to participate in this trial – a 30% increase in cod quota - has been criticised for potentially selecting for demersal trawlers with substantial cod quota [36], emphasising the importance of keeping in mind that other REM-experienced fishers using other gear types like gillnet, longline, pelagic trawl or seine may have different views than those expressed here. In all, interviewed REM-experienced fishers represented 29.0% of all Danish vessels participating in all REM trials and 50.0% of Danish REM trawlers.

2.5. Data handling

Responses from fishery inspectors were compiled manually after

Table 2
Gear type, fishing area, job title and target species of interviewed fishers.

	REM-experienced fishers, n=12	Non-REM-experienced fishers, n=10
Gear types	Trawl (n=12)	Danish seiner (n=1) Trawl (n=3) Industrial trawl (n=2) Gillnet (n=4)
Main fishing area	The North Sea (n=12)	Skagerrak (n=5) The North Sea (n=3) Kattegat (n=2)
Main target species	Mixed demersal, mainly *Nephrops*, plaice, cod, saithe, haddock and hake (n=12)	Plaice and cod (n=1) Cod, haddock, whiting and saithe (n=1) Sprat and sandeel (n=2) *Nephrops* (n=2) Cod, plaice, sole, hake and saithe (n=4)
Title	Skipper (n=9) Crew (n=3)	Skipper (n=6) Crew (n=4)

collection. Responses to close-ended questions were easily compiled whereas responses to open-ended questions had to be categorised in order to compare responses. Response categories were developed and fitted empirically in order to highlight the main points while avoiding removing important nuances. Although great care has been given to this process, it cannot be fully ruled out that the inherent interpretation taking place in such a categorising may reduce the scope of the collected data.

Responses from fishers were also categorised manually but as fishers' responses came during a live conversation, the interviewer's interpretation and categorisation of the responses were read to the fisher who could then acknowledge or reject and elaborate on the response. This check on responses was done during the interview to avoid misunderstandings.

As the respondents from both the fishery inspectors' group and the REM-experienced fishers' group represented at least 30% of their group, their responses were considered sufficiently representative to be treated quantitatively. The ten fishers without REM experience are a heterogeneous group and represent less than 0.5‰ of the approximately 4800 registered fishers in Denmark [37]. As such, their responses cannot be considered representative for all fishers in Denmark without REM experience but are included to extend and contrast views.

3. Results

3.1. Fishery inspectors' views on REM

In all, 80% of the interviewed fishery inspectors could say something positive about REM (Table 3), primarily pointing out its potential for full documentation and compliance with discard regulations (63%). However, 20% of fishery inspectors did not see any benefits in REM. Concerns on the use of REM revolved around the possibility to bypass the cameras, because REM is presented as a tool for full documentation, which almost 23% of the fishery inspectors did not believe REM will allow for. Additionally, the surveillance level was seen as an intrusion by 27% of the fishery inspectors.

Table 3
The positive, negative and overall opinion on REM, fishery inspectors.

		Fishery inspectors (n=30)	
Questions	Answers	N	%
Can you say something positive on REM with CCTV? (open ended question)	Should allow for full documentation	10	33.3
	Should ensure compliance with discard regulations	9	30.0
	No	6	20.0
	Has a preventive effect	3	10.0
	Can be expanded to form a reference fleet	1	3.3
	Relatively cheap control measure	1	3.3
Can you say something negative on REM with CCTV? (open ended question)	Can be bypassed for instance due to blind spots	8	26.7
	The surveillance level is an intrusion.	8	26.7
	It is not full documentation but people think it is	7	23.3
	Insufficient as the sole control measure	3	10.0
	Expensive	2	6.7
	Vulnerable to smudge or water droplets on the camera lenses	2	6.7
Are you generally for or against the use of REM with CCTV?	For	12	40.0
	Against	5	16.7
	Neither for nor against	13	43.3

Table 4
Average and median ranking for seven MCS measures, n=26.

MCS measure	Average rank	Median rank	Lowest rank	Highest rank[a]
On-board observer	2.1	1	7	1
At-sea control	2.3	3	4	1
REM with CCTV	3.2	3	6	1
Reference fleet	4.1	4	7	1
Control of landings	4.7	4	7	2
Logbook	5.4	5	7	3
Genetic control	5.8	6	7	2

The highest possible rank was 1, lowest possible rank was 7. Six of the 26 respondents were unfamiliar with genetic control. Two of the 26 respondents were unfamiliar with reference fleets as a MCS measure. All 26 respondents gave a score for on-board observers, at-sea control, REM, control of landings and logbooks.

[a] Lowest and highest rank refer to the lowest and highest rank given by any respondent.

In general, 17% of the fishery inspectors were against REM but with 40% of fishery inspectors being for the use of REM and 43% being undecided, the majority of fishery inspectors did not oppose REM as a MCS measure.

The fishery inspectors then ranked seven MCS measures (Table 4). Fishery inspectors could add other MCS measures in a subsequent open-ended question but the respondents proposed no other measures. Four of the 30 respondents completed the ranking in a wrong manner by giving the same score to several MCS measures or leaving blank cells. The scoring from these four respondents was excluded.

3.2. Fishery inspectors view on the landing obligation

More than 80% of the 30 fishery inspectors stated that enforcing the landing obligation was the main challenge as they did not see how it would be possible to control and thereby enforce the landing obligation (Table 5).

Most fishery inspectors were unsure whether the landing obligation would have a positive effect on the marine environment, but did not believe either that it may have a negative impact (Table 6).

The potential positive reasons given were the reduction in fishing mortality and the increase in selectivity if discarding ends. The negative reasons were non-compliance with the regulation or that the end of discarding would lead to a loss of available food sources among marine organisms which in turn may lead to a lower production. Additionally, fishery inspectors were asked on the positive and the negative effects of the landing obligation on the Danish fisheries (Table 7).

The potential positive reasons were a better public image and increased quota when discards were no longer included in the stock assessments.

The negative reasons were the increased complexity in regulations and the inherent mismatch between a continuation of the current quota system and a discard ban where choke species, increased handling time and shortage of storage space were mentioned as issues.

Table 5
Challenges for the fishery control with the landing obligation.

		Fishery inspectors (n=30)	
Question	Answers	N	%
What do you see as the primary challenge regarding the landing obligation, for the fisheries control? (open ended question)	Enforcing the landing obligation	25	83.3
	Getting the fishers to see why the landing obligation is meaningful	3	10.0
	No new challenges	1	3.3
	Did not answer	1	3.3

Table 6
Effect of the landing obligation on the marine environment.

Questions	Answers	Fishery inspectors (n=30)	
		N	%
Do you believe that the landing obligation will have a *positive* effect on the marine environment?	Yes	10	33.3
	No	7	23.3
	Do not know	13	43.3
Do you believe that the landing obligation will have a *negative* effect on the marine environment?	Yes	1	3.3
	No	19	63.3
	Do not know	10	33.3

Table 7
Effect of the landing obligation on the Danish fisheries.

Questions	Answers	Fishery inspectors (n=30)	
		N	%
Do you believe that the landing obligation will have a *positive* effect on the Danish fisheries?	Yes	13	43.3
	No	11	36.7
	Do not know	6	20.0
Do you believe that the landing obligation will have a *negative* effect on the Danish fisheries?	Yes	9	30.0
	No	13	43.3
	Do not know	8	26.7

3.3. Fishers' opinion on REM

Fishers' were asked the same questions on REM as fishery inspectors (Table 8).

All interviewed fishers who had participated in a REM trial could state something positive about the concept, mainly pointing to quota uplift, public goodwill and more sustainable fisheries. This is in contrast to the interviewed fishers without REM experience where the majority did not have anything positive to say regarding REM. As one non-REM experienced fisher responded: "*No. It is a waste of time and gives no results for the stocks*".

The issues with REM most frequently mentioned by REM-experienced fishers were the constant surveillance first, and as second the fact that all European vessels should carry REM. The current use of REM does not match well with "*an equal playing field*" if not all EU vessels have a REM system installed. The surveillance level was also the main issue raised by non-REM-experienced fishers but even though the issue was the same, non-REM-experienced fishers expressed their disapproval in stronger wordings than REM-experienced fishers, with a tendency to emphasise that they perceived REM as a criminalisation of the fishing industry. As one non-REM-experienced fisher put it: "*It is idiotic! Are fishers criminals?* ".

Non-REM-experienced fishers also criticised REM for being a waste of time that can be misused to discredit the industry and a few stated that the trials are skewed and therefore cannot be used for anything. Specific criticisms of the trial setups were also pointed out as issues among REM-experienced fishers, such as an inadequate feedback on trial results. One REM-experienced fisher came with possibly the one response that best illustrate that some REM-experienced fishers do not perceive major issues with REM, simply responding in a humoristic manner that the main negative aspect of REM was that they could no longer high-grade.

Except for one who was undecided, all interviewed non-REM-experienced fishers were against the use of REM, whereas the majority of interviewed REM-experienced fishers were for the use of REM. However, some sort of reward should accompany the REM system (Table 9). As a REM-experienced fisher put it: "*If it was up to me everyone should have REM on-board. But we want something for having cameras on-board.*"

Table 8
The positive, negative and overall opinion on REM, fishers' responses.

Questions	Answers	REM-experienced fishers (n=12)		Non-REM-experienced fishers (n=10)	
		N	%	N	%
Can you say something positive about REM with CCTV? (open ended question)	Quota increase	5	41.7	1	10.0
	No/Nothing	0	0.0	6	60.0
	Increase in public goodwill/image improvement	3	25.0	0	0.0
	Induce adaptions for more sustainable fisheries	3	25.0	0	0.0
	REM can catch those who cheat	0	0.0	3	30.0
	Better stock assessment	1	8.3	0	0.0
Can you say something negative about REM with CCTV? (open ended question)	Surveillance is a criminalisation of the industry	0	0.0	4	40.0
	Constant surveillance	4	33.3	0	0.0
	Nothing particular but should apply to all European vessels	3	25.0	0	0.0
	REM trials are skewed since extra cod quota changes the target species for participants	0	0.0	2	20.0
	REM is waste of time with no actual effect	0	0.0	2	20.0
	Video footage can be misused	0	0.0	1	10.0
	Inadequate feedback from REM project	1	8.3	0	0.0
	Too expensive since extra quota have been necessary to be bought due to regulations on CQM	1	8.3	0	0.0
	Result of micromanagement which is harsh for the fishing industry compared to the agricultural sector	1	8.3	0	0.0
	Vessels participating in REM trials have become dependent on the extra quota	1	8.3	0	0.0
	We can't high-grade	1	8.3	0	0.0
	No	0	0.0	1	10.0
Are you generally for or against the use of REM with CCTV?	For	7	58.3	0	0.0
	Against	4	33.3	9	90.0
	Undecided	1	8.3	1	10.0

Quota uplifts were clearly favoured as a compensation for REM, although the possibility to store bycatch as ensilage and less technical rules (free gear choice) were mentioned as well by REM-experienced fishers. In contrast, no non-REM-experienced fishers would take REM on if free selection of gear was the only reward. Although some non-REM-experienced fishers were willing to take on REM if this was accompanied by a quota uplift, other non-REM-experienced fishers were quite passionate in stating that no reward could ever mitigate the nuisance of having REM on-board. Quoting one of these respondents: "*The question is not relevant. A quota increase cannot be great enough for me to be willing to sell my soul*".

3.4. Fishers' opinion on the landing obligation

Interviewed fishers were generally quite negative in their opinion

Table 9
Fishers' willingness to take on REM depending on the accompanying benefit.

Questions	Answers	REM-experienced fishers (n=12)		Non-REM-experienced fishers (n=10)	
		N	%	N	%
If REM gave the right to free selection of fishing gears, would you then take cameras on board?	Yes	2	16.7	0	0.0
	No	8	66.7	10	100.0
	Did not answer	2	16.7	0	0.0
If REM gave an increase in quota, how large would such an increase have to be for you to take cameras on board?	20%	2	16.7	0	0.0
	30%	7	58.3	4	40.0
	100%	0	0.0	1	10.0
	No quota increase could be large enough	1	8.3	4	40.0
	Did not answer	2	16.7	1	10.0

on the landing obligation. Fishers did not only fear the economic profitability of their sector after the introduction of the landing obligation; they were also largely confused and felt harassed stating that they expected an increase in bureaucracy with incoherent regulations as a result. As one non-REM-experienced fisher stated: "*We don't know what is going on. There is no description. We are not allowed to land it (the catch, red.) and we are not allowed to discard. What do they want us to do with it?*".

Some of the responding REM-experienced fishers were less worried of the impact of the regulation, with one respondent stating to a question on whether they had done or would make any specific preparation prior to the implementation of the landing obligation for their fishery: "*No. We have nothing to hide and can handle it*".

However, the majority of interviewed fishers, regardless of gear or experience with REM, believed that the landing obligation would have a negative effect on the Danish fisheries due to issues with choke species, storage space, handling time, quota settings and marketing. All these issues were believed to hamper the economic sustainability of the fisheries. Additionally, hardly any interviewed fisher (1 out of 22) believed the landing obligation would have a positive effect on the marine environment. Indeed, the majority of interviewed fishers believed that rather than improving the status of the marine environment, the landing obligation would be damaging to the marine environment (15 out of 22). Reasons given for this were the increased mortality for fish that would have survived discarding (but will be taken ashore with the landing obligation) and the decrease in available food sources for organisms that feed on discards, be it seabirds, other fish or benthic organisms. A few other responding fishers (6 out 22) did not see the landing obligation as having neither a negative nor a positive effect. These respondents see the landing obligation as indifferent. Quoting one of these respondents, an industrial trawl fisher who had already been operating under the landing obligation for almost one year: "*It (the landing obligation red.) is just another type of documentation. The fishing practice is not changed as such.*"

4. Discussion

4.1. Opinions on REM

The practical knowledge on REM was not homogenous among responding fishery inspectors as almost one third had no REM experience and another third had only encountered REM while performing at-sea control on a REM vessel. Only four out of the 30 responding fishery inspectors had actually reviewed video footage from REM systems. This does not mean that the take on REM is unimportant for the majority of fishery inspectors but it should be kept in mind that most of the fishery inspectors have little if any practical experience with REM and therefore may have been influenced in their beliefs from talks on REM with co-workers or fishers.

Among fishery inspectors, the possibility to cheat REM by bypassing the CCTV field of view was widely seen as a downside with this system, not least on the basis that REM is presented as being a reliable tool for achieving full documentation. The other major issue perceived with the use of REM is the intrusiveness of cameras. The risk of smudge sticking to camera lenses and the cost of operating a fisheries monitored by REM were also raised as issues, although, other fishery inspectors pointed to the opposite opinions arguing for the lower cost and better level of control as the possible gains from REM. This suggests either quite divergent perceptions of the outcomes of the Danish trials on REM among fishery inspectors in Denmark or that the questionnaire setup has increased the divergence on the subject. Because the opinion on REM was investigated both with a question on the positive and a question on the negative aspects of REM in the questionnaire, this could have led to positive and negative responses on REM from respondents who may have only stated a positive or negative aspect if responding to a single open-ended question on their general opinion on REM.

Globally, fishery inspectors viewed at-sea control and on-board observers as superior MCS tools compared to REM, but only at-sea control had a low spread in the scoring between the individual fishery inspectors indicating high convergence. The positive opinion on at-sea control might however be somewhat influenced by the respondents, since several responding fishery inspectors perform at-sea control in their daily work and thereby might be inclined to favour this measure. Despite this, REM was ranked as the third best option out of seven possible, had the same median ranking as at-sea control and scored a top ranking among several of the respondents. The overall opinion on REM among fishery inspectors is thus quite divergent. One in six fishery inspectors stated they are against the use of REM and two almost equally large groups were either "for" or "neither for nor against" the use of video documentation. It may be kept in mind that the large group of fishery inspectors who stated "neither for nor against" to the question on their general opinion towards REM, may be influenced in their response by their position as government officials. Because the final decision on the use of REM is political, some responders may find it inappropriate to take position for or against this MCS measure. This could also explain why six fishery inspectors had nothing positive to say about REM whereas five stated they were against the measure. The political opinion has previously been in favour of REM in Denmark [38,39], however the current administration has not been clear in its support of REM.

Interviewed fishers in favour of REM added that a reward should accompany the REM system, and pointed to quota uplifts as the preferred option. The fact that Danish trials on REM has been voluntary and have been conducted mainly with a quota premium as the reward may have influenced the views of REM-experienced fishers. The responses are however in line with the report by Hedley et al. (2015) that stated that due to the voluntary nature of the trials using REM it is difficult to infer how REM would work if it would become compulsory for all vessels, with no quota premium given as compensation [8]. While none of the non-REM-experienced fishers were supportive of the use of REM, it is worth noting that the majority of REM-experienced fishers were supportive of it. Based on this study it cannot be inferred whether these fishers were positive towards REM as a MCS measure before they started in a REM trial. However, it can be said that participation in a REM trial has not led to a general antipathy towards the measure.

4.2. Opinions on the landing obligation

The majority of responding fishery inspectors stated that the largest challenge for the fishery control with the landing obligation will be to actually enforce the regulation. Current Danish fishery control uses at-sea control, landings control and self-reported catches in the electronic logbook to perform a risk-based management [40,41]. With the majority of fishery inspectors fearing that the landing obligation cannot be enforced properly, it seems that these methods are believed to be insufficient as tools to verify total catches and not just landings. Though the majority of responding fishery inspectors believed the landing obligation will have a positive effect on the marine environment, a large group of respondents were nevertheless doubtful as to what will happen. Concerns were raised on the impact of removing the "free" food source that discards act as. Fishery inspectors were less certain as to whether this effect will be negative for the ecosystem than the responding fishers were. The true ecological effect of removing discards is unclear. Some studies have pointed to the reduced food availability as a potential negative effect of reduced discards, especially for seabird populations and primary scavengers [42–44], although the actual effects up the food chain and in the long-term effects are uncertain but likely limited [4,45]. The effect of reducing the food source from discards depend on several factors and the potential increase in selectivity and reduced fishing mortality are likely to mean a net positive effect on fish stocks [42,43].

Regarding the effect on fisheries, a third of fishery inspectors expressed confidence in the adaptability of the industry and the effect of a better public image, but another third of them believed the landing obligation will have a negative effect on the Danish fisheries, mainly due to increased complexity and mismatch in regulations.

The notable resentment towards the landing obligation among responding fishers together with the fishery inspectors' disbelief in a viable control and enforcement of the regulation raise concerns. Compliance behaviour among fishers has been found to be influenced by whether regulations are seen as meaningful and legitimate [46–48]. In an earlier Danish study, it was found that if fishers begin to violate regulations, it can create a shift in the attitude towards a regulation, were non-compliance may become the norm rather than the exception [47]. Interestingly, that study reported fishers to find it morally wrong to discard catches that are dead [47], whereas this ethical aspect did not appear strongly in the present interviews.

No difference in the attitude towards the landing obligation based on gear, target species or fishing area was presented in this study because no such difference was found. One might have expected to see a lower resentment towards the landing obligation among fisheries with a high selectivity, like gillnetters. However, that this is not seen in this study may both be due to the low number of responding fishers using gillnet and the general uncertainty among fishers as to how the landing obligation will be when it is fully implemented.

4.3. REM and the landing obligation

Based on the responses regarding the landing obligation there seems to be a need for MCS measures if compliance is to be ensured. Article 15 in the 2013 CFP state that:

> "*For the purpose of monitoring compliance with the landing obligation, Member States shall ensure detailed and accurate documentation of all fishing trips and adequate capacity and means, such as observers, closed-circuit television (CCTV) and others. In doing so, Member States shall respect the principle of efficiency and proportionality.*" [13].

Looking at the more technical criticism raised by responders in the present study, the shortcomings portrayed for REM focused on the cost of running a REM system, malfunctions and that the system does not truly ensure full documentation. All of these points are valid, but should be kept in comparison with the alternative MCS measures. The workload and thereby cost of auditing video footage can be reduced by doing samples, as has been the case in the Danish Cod Catch Quota Management trial [14,49]. Hereby a certain percentage of the total video footage is reviewed. This percentage can be lowered or increased depending on factors like available funds and the level of control deemed adequate. If non-compliance or suspicious behaviour occur in the sampled footage, the amount of reviewed data can be increased to comprehensively document potential non-compliance. Fitting REM onto vessels and recording all fishing activities does not automatically mean reviewing all the video footage. It is therefore more accurate to compare the level of control with those obtained with current control measures, like at-sea control and on-board observers. With such a comparison both the cost and the workload involved in reviewing video footage seems less cumbersome and is likely to be cheaper [15,16,23,50]. Additionally, because of the random selection procedures often used in REM trials, the fishers do not know which footage will be selected for review. This mean that although only a certain percentage of the video footage is reviewed, essentially REM allow for 100% monitoring coverage of fishing activities which would be very costly to obtain with on-board observers [14,16,23].

Finally, the technology is in constant development, and there are great potentials for achieving full review of all video footage in the future using automated image analysis [23,32]. The technology is nowadays still vulnerable to dirt on camera lenses, distortions in the field of video view and periods where large quantities of fish occur on the discard belt [32]. However, further development may enable video audit to be done mainly by computer software, supported by trained personnel in order to determine the course of action when the computer software is unable to distinguish or if malfunctions occur.

The possibility to bypass REM and practice non-compliance cannot be dismissed. However, this is also true for other MCS measures like at-sea control or landings control, because these measures only allow for limited or no presence during the handling of catches at sea. For a given haul, using on-board observers is likely to ensure better data and a higher degree of full documentation than REM, because observers can perform additional measurements, which are not possible with a video system, and observers are less likely to be affected by blind spots during catch processing [16]. Discrepancies between observers, fishers estimates and REM data may still occur, especially when the quantities observed are small [14,24]. The reasons for these discrepancies must be carefully investigated and the estimation protocols adapted if necessary. Nevertheless, it must be noted that in many cases, these discrepancies lead to uncertain but not necessarily biased estimates [14,24]. While it might always be possible to bypass a REM system, it may also be relevant to speculate whether and when it is profitable for a fisher to bypass the system? If the perceived effort to bypass the MCS measure is greater than the perceived gain from non-compliance, it would make more sense simply to comply with the regulation. In the Danish Cod Catch Quota Management trials, self-sampling estimates were often higher than estimates from video audit, even though the reported discards were deduced from the quota [14,51] This could indicate that compliance was generally perceived as more beneficial than non-compliance. If so, self-sampling verified by REM has fulfilled its purpose, regardless of whether the REM system can be bypassed or not.

Possibly the largest reservation against the use of REM is the ethical dilemma it presents. The strong resentment towards the surveillance level is the main weakness of REM [3,16]. Rather than making REM compulsory it may be easier to establish a voluntary reference fleet where self-reported catches are verified by REM. As in the Norwegian reference fleet, the benefit for vessels could be quota uplifts [16]. Alternatively, it has been suggested to use a *quid-pro-quo* approach where fishers who agree to have a high level of MCS that allow for accurate catch data are rewarded with higher quotas than fishers who chose to be under less extensive MCS [52]. The logic behind is that it should count in one's favour to provide accurate catch data whereas those not willing to provide accurate catch data are assumed to continue with a certain level of discarding which is then reflected in their quota. The actual use and ownership of video footage may also improve fishers' opinion on REM. Using the practice for trucks' black boxes as a model, clear division and rules underlining that fishers has the ownership of REM data would minimise the risk of third parties getting hold of video footage and use it to discredit the fishing industry, an issue which fishers pointed to both in this survey and in a UK study [16]. For MCS purposes, the fisheries control authorities could ask for video documentation by the fisher in question in cases where non-compliance were suspected, thus reversing the burden of proof and bringing the responsibility back to the fishers.

If REM is ruled out as a MCS measure, it will be necessary to ensure compliance by some other mean. Creating economic incentives that make rule compliance more favourable than non-compliance might be possible, e.g. by utilization of fish below the Minimum Conservation Reference Size [42]. However, this approach is a delicate balance, because the possible profit gained from utilization has to be at level where it does not counteract the incentive for good gear selectivity [4,42,44]. The use of on-board observers has the potential to ensure compliance with the landing obligation, but the extent of such a MCS measure is likely to be very costly. Additionally, making on-board observers mandatory may also be seen as an intrusion just like the use of REM. In the North Pacific, McElderry reported REM monitored fishers to prefer REM over on-board observers as the presence of cameras were seen as less intrusive [53].

5. Conclusion

The responses from interviews and questionnaires point to great uncertainties regarding the perceived effects of the landing obligation and whether the landing obligation will be complied with. Not only does it appear that the regulation is often not perceived as meaningful in the Danish fishery community, it is also largely seen as impossible to enforce by the fishery inspectors. This mistrust will clearly be a major hindrance to the full implementation of the landing obligation. The use of REM is considered as a mean to ensure compliance and to document whether fishers exploit the marine resources in a sustainable manner. However, the mandatory use of REM is likely to be met with opposition from the fishing community. On the other hand, it is worth noting that the majority of fishers who had participated in a REM trial did not display strong antipathy against REM. In addition, the majority of fishery inspectors believe that the landing obligation cannot be enforced properly, meaning that the current methods of at-sea and at-port control are perceived as inadequate for the control of total catches. The mandatory use of on-board observers will likely be very costly, and may neither be considered positively by the fishing community. In parallel with extending and enhancing MCS measures, it is therefore crucial to design incentives for compliance [9]. There are many different approaches and combinations of MCS measures, which could come into play as means to verify compliance with the landing obligation [8,11,33], and different options might be suitable in different fisheries. In the frame of the increased regionalisation framed by the 2013 CFP, increased dialogue between managers, fishers, controllers and scientists is taking place within each Member State, hopefully paving a way for future fisheries management that is both legitimate and effective.

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Paper II - Unravelling the scientific potential of high resolution fishery data

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RESEARCH ARTICLE

Unravelling the scientific potential of high resolution fishery data

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Abstract – Fisheries science and fisheries management advice rely on both scientific and commercial data to estimate the distribution and abundance of marine species. These two data types differ, with scientific data having a broader geographical coverage but less intensity and time coverage compared to commercial data. Here we present a new type of commercial data with high resolution and coverage. To our knowledge, the dataset presented in this study has never been used for scientific purposes. While commercial datasets usually include the total weight by species on per haul basis, the new data also include the commercial size class for the species landed, recorded directly on a haul-by-haul basis. Thus, this dataset has the potential to provide knowledge on landed fish with as high spatio-temporal resolution as when coupling logbooks and sales slips but with the addition of detailed knowledge on the size distribution. Such information may otherwise be obtained through on-board observer programmes but unlike the observers' data, the dataset presented here is routinely collected on most of the trips of the vessels involved, which means that the coverage of the data for the individual vessel is larger than observers' data. Furthermore, the risk of changes in fishing behaviour due to the presence of an observer on-board is avoided. This paper describes the coverage and completeness of the dataset, and explores the reliability of the data available. We conclude that the main limitation is the small number of fishing vessels covered by the program, but that the data from those vessels are accurate, detailed, and relatively reliable.

Keywords: Fisheries / haul-by-haul information / science-industry cooperation / sea-packing commercial fishery data / size distribution / spatial and seasonal selectivity

1 Introduction

Fisheries science and management rely on scientific survey data and commercial fishery data to estimate the status of marine populations and assess the impact of fishery on the environment. A key challenge is that the two data sources differ much in quality and detail. Scientific survey data usually have a broader and more homogeneous geographical coverage than commercial fishery data, as fishers target certain species and areas. However, scientific survey data have less intensity and temporal coverage (Pennino et al., 2016; Bourdaud et al., 2017). While both commercial and scientific data are important sources of information, it is a challenge to link the two types of data and provide a coherent picture (Poos et al., 2013; Bourdaud et al., 2017). Currently, integrated commercial datasets rely on coupling data from logbooks, sales slips and the vessel monitoring system (VMS) to allocate landings to vessels' hauls and fishing grounds (Hintzen et al., 2012). However, size composition at haul level is not known, and it is usually assumed that it is the same as the aggregated size composition from the entire trip (Bastardie et al., 2010). Fishing trips can cover several days and large areas, with potentially large variation in size composition; hence, these estimates probably introduce a bias. Thus, expanding the commercial data to incorporate accurate recordings of size at haul level could add significant quality to the information available (Verdoit et al., 2003; Bourdaud et al., 2017). A Danish initiative of packing-at-sea came to our attention that might be able to provide such information. The project started in 1995 with the purpose of investigating whether sea-packing could provide additional profit to fishers, by reducing their costs of size-sorting and packing at the auctions, and by ensuring higher quality fish. The project found a reduction in costs of 6–7% when packing fish at-sea but remained inconclusive on whether sea-packing resulted in a profit increase (Frederiksen and Olsen, 1997; Frederiksen et al., 2002). Because sea-packed fish are labelled with information

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on size class, species, weight, vessel, and catch time, a by-product of this project was the development of a database collecting the size composition of landings at the haul level together with detailed spatio-temporal information. Although on-board observers programmes in the EU collect data with similar resolution and characteristics, the sea-packing data extends the data coverage substantially because vessels engaged in sea-packing record their sea-packed landings for most trips, while observers only record a limited number of trips. Additionally, sea-packing data are collected by fishers, without additional costs to be borne by scientists or public authorities.

In 2002, the Council of the European Union laid down rules for increased traceability of food goods, including fish (EU, 2002). The traceability regulations apply for batches of fish, with a batch being a quantity of fish caught at one time. The regulations do allow for the registration of a batch as the compiled landings from a full fishing trip. Additionally, spatial traceability regulations are complied with if a batch can be traced to the fishing area (e.g. an ICES subdivision) which covers large areas. In Denmark three traceability systems were developed to meet the requirements; the Vessels Data Exchange Center (VDEC) software, the yellow catch information notes and the "Sporbarhed i Fiskerisektoren" (SIF) database, which is an add-on to the sea-packing project. The VDEC is in theory capable of delivering more detailed data than the electronic logbook (eLog), including crate landing composition and size classes (a crate is a standard size box used to store fish for landing (Pack and Sea A/S, 2018)). However, in practice, most of the data reported in the VDEC are limited to haul position, time, and non-sized landings information (O. Skov, personal communication). The yellow catch information notes were developed by the industry to ensure compliance with the regulations among vessels unfit for carrying sea-packing or VDEC equipment (Dandanell and Vejrup, 2013). A note is filled in for the crate with information of the fishing trip including date of first and last fishing, geographical area where fishing took place (as ICES subdivision), gear type and other administrative information, as well as the species and commercial size class. The minimum labelling and information requirements are thus complied with (EU, 2001, 2009, 2011; Dandanell and Vejrup, 2013).

The present study focus on the third system, the SIF database. We analyse and explore the accessibility, coverage, consistency and reliability of the data, in order to assess whether it may be used for scientific studies and in management advice. The quality of the data is assessed by comparing it with the eLog, sales slips and data from a trial using Remote Electronic Monitoring with a camera system (EM). The objective of the present paper is only to investigate whether SIF data are suitable and reliable, before they can be used in future studies. As such, we primarily focus here on describing these new data and assess their quality. Future studies involving SIF data are briefly suggested, including comparison with coupled VMS and logbook data as well as studies on spatial size distribution for certain species.

2 Materials and methods

2.1 The SIF database

The SIF database began in 2012 as collaboration between the Danish Fishermen's Association (DFPO), the Danish AgriFish Agency and the retail industry. The sea-packing data in SIF provide information at haul level on the landed species and size composition by weight, together with detailed information on date, time and position of the haul. The size classes applied are those defined by the EU regulation and size classes used by the fish auctions (Tab. 1) (EU, 1996; Danske Fiskeauktioner, 2017). The sea-packing equipment includes a dynamic scale, which records the weight of each size class of each species automatically. When in port, the records are relayed online from the sea-packing software to SIF. The weight recorded by the sea-packing equipment is the gutted weight, not the live weight as recorded in the eLog (Frederiksen et al., 1997, 2002; Danish AgriFish Agency, 2017). As in the eLog, the SIF database allows for entries of discards in addition to the landings. Figure 1 presents a schematic of the difference between landings information at haul level in the eLog and SIF. SIF provides the size composition of the landings directly at haul level, assuming that the sea-packed fish of a given species are representative of the total landings of that species in the individual haul. This assumption will be discussed in the subsection *Using SIF data*. SIF is linked with the eLog, from which the temporal and spatial data for the hauls are derived. In 2016, funding for SIF operational costs was reduced. The future of SIF is thus uncertain, although it recently proved valuable. In 2017, the German authorities required traceability data for a batch of fish a German buyer had purchased from a wholesaler in Denmark. The required information could be retrieved from in SIF and met the expectations of the German authorities, thus demonstrating the operationality of the system (C.S. Pedersen, personal communication).

2.2 Data collection

As each vessel owns its own data in SIF, individual acceptance to use the data for the present study was required. Around 90 vessels operated with sea-packing in Denmark in 2015 and 2016. All sea-packing vessels were part of the large-scale fleet, which consisted of 419 vessels in 2015 and 396 vessels in 2016 (STECF, 2017). However, due to confidentiality agreements, vessel details from SIF could not be provided by the database administrator (C.S. Pedersen, personal communication). Twenty eight vessel owners have thus been personally contacted so far, and asked whether they sea-pack their landings and are willing to grant access to their SIF data. At the time of writing, confirmation was still pending from four skippers, 13 skippers had granted access to their SIF data and 11 skippers had refused (Tab. 2). The access to SIF occur through a website, with no export function. A web scraper was thus developed to extract the data.

2.3 Study period

The study period is January 1 2015–December 31 2016. Over this period, high resolution haul data for five vessels and SIF data could be compared with EM data (GPS) for two vessels, which both had sea-packing equipment and participated in the Danish Cod Catch Quota Management trial (Ulrich et al., 2015; Bergsson and Plet-Hansen, 2016; Bergsson et al., 2017).

Table 1. Commercial fish size classes and their corresponding weight in kg for the 10 investigated species based on SIF and Danish fish auction as well as DFAD and EU regulations.

Species	Size class, SIF/Danish fish auction	Weight range [kg/fish]	Size class, DFAD/EU regulation	Weight range [kg/fish]
Cod	0	>10.00		
	1	7.00–10.00	1	>7.00
	2	4.00–7.00	2	4.00–7.00
	3	2.00–4.00	3	2.00–4.00
	4	1.00–2.00	4	1.00–2.00
	5	0.30–1.00	5	0.30–1.00
Hake	0	>4.00		
	1	2.50–4.00	1	>2.50
	2	1.20–2.50	2	1.20–2.50
	3	0.60–1.20	3	0.60–1.20
	4	0.28–0.60	4	0.28–0.60
Plaice	1	>0.60	1	>0.60
	2	0.40–0.60	2	0.40–0.60
	3	0.30–0.40	3	0.30–0.40
	4	0.15–0.30	4	0.15–0.30
Haddock	1	>1.00	1	>1.00
	2	0.57–1.00	2	0.57–1.00
	3	0.37–0.57	3	0.37–0.57
	4	0.17–0.37	4	0.17–0.37
Saithe	1	>5.00	1	>5.00
	2	3.00–5.00	2	3.00–5.00
	3	1.50–3.00	3	1.50–3.00
	4	0.30–1.50	4	0.30–1.50
Lemon sole	1	>0.60	1	>0.60
	2	0.35–0.60	2	0.35–0.60
	3	0.18–0.35	3	0.18–0.35
Monkfish	1	>8.00	1	>8.00
	2	4.00–8.00	2	4.00–8.00
	3	2.00–4.00	3	2.00–4.00
	4	1.00–2.00	4	1.00–2.00
	5	0.50–1.00	5	0.50–1.00
Turbot	1	>3.00	1	>3.00
	2	2.00–3.00	2	2.00–3.00
	3	1.00–2.00	3	1.00–2.00
	4	<1.00	4	<1.00
Witch flounder	1	>0.50	1	>0.50
	2	0.30–0.50	2	0.30–0.50
	3	0.10–0.30	3	0.10–0.30
Wolffish	1	>3.00	1	>3.00
	2	1.00–3.00	2	1.00–3.00
	3	<1.00	3	<1.00
All species	**9**	**Unsorted**	**9**	**Unsorted**

2.4 Assessing validity of SIF against DFAD and eLog

For the validity assessment, SIF data from vessels A, B, C, D and E in 2015 and 2016 were compared to the DTU AQUA DFAD (Danish Fisheries Analyses Database) dataset. DFAD is based on sales slips merged with the eLog catches and fleet register data. Catches are recorded as total live weight of each species and since 2015 it has been mandatory to record catches in the eLog on a haul-by-haul level (EU, 2011; Danish AgriFish Agency, 2017). The coupling of eLog haul data and sales slips data do allow for inference of landings' size composition at the haul level assuming constant size distribution across all hauls (Bastardie et al., 2010; Hintzen et al., 2012). However, the assumption of even size distribution risks assigning inaccurate size distributions to the haul.

Not all species landed by a vessel are sea-packed. To analyse the completeness of the SIF data the species recorded in SIF were compared to the same vessels' data from DFAD. The 10 most important species (in landings by weight) for the five vessels were identified based on DFAD landings records. These 10 species constituted 95.8% of the landings by weight for the five vessels in both years. The completeness of landings recorded in SIF compared to DFAD was calculated as:

$$C_L = 100 - \frac{L_{\mathrm{DFAD}} - L_{\mathrm{SIF}}}{L_{\mathrm{DFAD}}} 100, \tag{1}$$

where L is the sum of recorded landings of the species in DFAD and SIF respectively. No conversion factor was needed for the comparison, since both SIF and DFAD have records of the gutted weight.

Similarly, the completeness of hauls available in SIF was estimated based on the number of hauls according to the eLog, using:

$$C_H = 100 - \frac{H_{\mathrm{eLog}} - H_{\mathrm{SIF}}}{H_{\mathrm{eLog}}} 100, \tag{2}$$

where H is the number of recorded hauls in eLog and SIF respectively.

A comparison between SIF and DFAD of the species and commercial size classes recorded by vessel A, B, C, D and E during 2015 and 2016 for the 10 most landed species was then performed. SIF and DFAD data were merged based on the trips' landing date. The weight of each commercial size class of the 10 most landed species for each trip was summed based on the unique logbook number identifying each fishing trip. Trips with no records in either SIF or DFAD were excluded. The largest size class for cod (*Gadus morhua*) and hake (*Merluccius merluccius*) in SIF is 0, whereas the largest size class is 1 in DFAD (Tab. 1). The division between the second largest size class, size class 2, and size class 1 is the same for SIF and DFAD. Therefore, size class 0 was aggregated with size class 1 in SIF to render the comparison between databases possible. In addition to a visual comparison of SIF and DFAD data at trip level, the fit between SIF and DFAD records was analysed with a linear model using the *lm* function in *R*. This was done to estimate how close SIF records are to DFAD records and vice-versa. A log-transformation was applied to

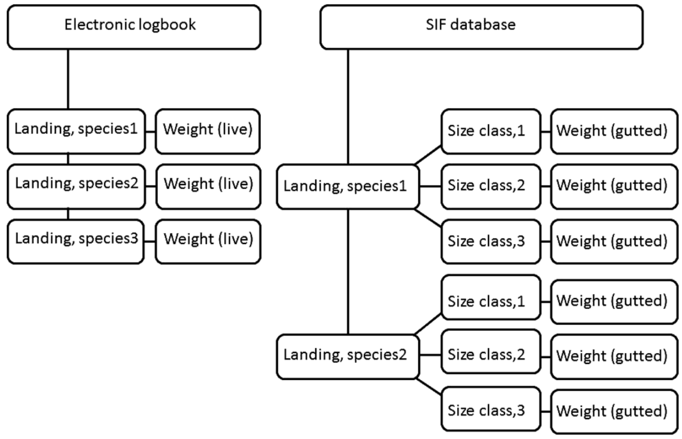

Fig. 1. Conceptual figure of the difference between landings data available at haul level in the electronic logbook and the sea-packing data available in the SIF database.

landings recorded in SIF and DFAD whereby normal distribution was induced.

The model is thus written as:

$$\log(y_i) = a + \log(x_i)b, \qquad (3)$$

where a is the intercept, b is the slope, y is the landings by size class recorded in SIF, x is the landings by size class recorded in DFAD and i is an index for the fishing trip and commercial size class of the investigated species.

Essentially, DFAD should contain all landings of all species from all the vessels' fishing trips. SIF has only records of all landings of all species from when the vessel started sea-packing during the fishing trip. A comparison of the trip-based percentwise size class compositions of landings was performed between trips where sea-packing did not take place and trips where sea-packing was conducted. This was done to investigate whether a potential bias in the size class compositions is possible depending on whether a vessel packs at-sea or not. The comparison was made solely using DFAD, because SIF does not have information in trips without sea-packing. First, the size class composition of the landings recorded in DFAD was calculated as a percentage of the total landings recorded in DFAD for trips where SIF records also existed and for trips where SIF records did not exist. This was plotted and investigated visually. Then, a non-parametric analysis was performed using the Wilcoxon rank-sum test, to detect potential bias in size distribution which could occur if fishers for instance only sea-pack at trips with ample volumes of large fish.

To investigate the effect of year, vessel and size class on the differences between landings recorded in SIF compared to DFAD, an extension of the model in equation (3) was made and analysed using an analysis of covariance (ANCOVA). The model is written as:

$$\log(y_i) = \log(x_i) + \beta_1(\mu_i) + \beta_2(\nu_i) + \beta_3(s_i), \qquad (4)$$

where y is the landings by size class recorded in SIF, x is the landings by size class recorded in DFAD, i is an index for the fishing trip, μ is year, ν is vessel, s is size class and β_1 to β_3 are the effects of year, vessel and size class for the investigated species.

2.5 Spatial distribution of SIF data compared to EM data

Because the SIF system depend on the eLog for the temporal and spatial haul information, a geographic comparison with DFAD is not relevant. Therefore, coverage quality was assessed using a different dataset, comparing SIF with the GPS sensor data from an EM trial run by the Danish AgriFish Agency in 2015 and 2016 (Bergsson and Plet-Hansen, 2016; Bergsson et al., 2017). This was done for two vessels that took part in this trial during 2015 and 2016. EM GPS data were plotted as dots at a 1-minute interval. Start and end position according to SIF was used to plot lines for each haul on the same chart. Because this assumes linear track courses, some deviance is expected. Additionally, some hauls with unrealistic haul lengths and towing speeds were spotted in SIF. SIF hauls were excluded if the towing speed exceeded 7 knots. The criteria for exclusion was based on information from the vessel owners on their maximum and usual towing lengths as well as an inspection of the maximum towing speeds recorded in the EM trial. In addition to the visual inspection, the mean mid-latitude and mid-longitude were calculated for each haul. Because fishers target certain fishing grounds, the distribution of fishing hauls becomes non-random and it is not possible to induce normal distribution of samples. Therefore, statistical comparison of mid-latitude and mid-longitude was performed using a Wilcoxon rank-sum test.

3 Results

Although it is possible to enter discards in SIF, none of the investigated vessels had any discards recorded. Seven of the 13 skippers who granted access to their SIF data had recordings at the haul level with high resolution, while the data from the other six showed that on these vessels, the sea-packing equipment was not used in a manner where the size classes were recorded at the haul level. The main reason given for this was that the vessels had

Table 2. Vessel ID, remarks and whether access to SIF data has been granted for contacted vessels. 4.a = Northern North Sea, 4.b = Central North Sea, 3.a = Skagerrak and Kattegat, 22–28 = Baltic Sea. Vessels where owners were unwilling to share SIF or who are undecided have been aggregated into groups based on reason for not granting access or remark on current status.

Vessel	Access granted	Usable haul data	Main fishing areas	First entry at haul level	Remarks
A	Yes	Yes	4.a, 4.b, 3.a	10-04-2015	Number of hauls in SIF 2015–2016: 1473
B	Yes	Yes	4.a, 4.b, 3.a	27-03-2014	Number of hauls in SIF 2015–2016: 925
C	Yes	Yes	4.a, 4.b, 3.a, 22–28	09-12-2013	Number of hauls in SIF 2015–2016: 928
D	Yes	Yes	4.a, 4.b, 3.a	20-03-2015	Number of hauls in SIF 2015–2016: 1418
E	Yes	Yes	4.a, 4.b, 3.a	19-12-2013	Number of hauls in SIF 2015–2016: 1062
F	Yes	Yes	4.a, 4.b, 3.a	19-10-2016	Number of hauls in SIF 2015–2016: 118
N1	No				Believe it to be too expensive in time and money to look into their SIF data
N2, N3	No				No reason given
N4, N5	No				Only sea-pack hake. Did not see the use of sharing the data for one species
N6–N10	No				Use the sea-packing machinery to clean the fish and report to the eLog
N11	No				Was uncertain as to whether the data could be misused
U1–U4	Undecided				Waiting for email confirmation
Q	Yes	No	4.b, 3.a, 22–28	None	Only sales slips records in SIF
T	Yes	No	4.a, 4.b, 3.a	08-05-2012	Stop sea-packing in January 2015 due to change in vessel ownership
V	Yes	No	4.b	None	Gillnetter. No hauls. Sea-packing is recorded at day level
W	Yes	No	4.b, 3.a	05-12-2013	Use the sea-packing machinery to clean the fish and report to the eLog
X	Yes	No	4.a, 4.b, 3.a, 22–28	20-12-2013	Manually enter haul positions and time. Haul positions and timestamps are unreliable
Y	Yes	No	4.a, 4.b, 3.a, 22–28	17-12-2013	Use the sea-packing machinery to clean the fish and report to the eLog
Z	Yes	No	4.a, 4.b, 3.a	02-12-2013	Use the sea-packing machinery to clean the fish and report to the eLog

used the sea-packing equipment to clean the fish during their catch processing but had not stored their landings in size-graded crates (Tab. 2). This was also the main reason given by the 11 skippers who have not granted access.

3.1 Species not occurring in SIF

Of all species reported in DFAD for each vessel, only a few were never reported in SIF. For vessel A, this was the case for five species: Atlantic mackerel (*Scomber scombrus*), edible crab (*Cancer pagurus*), marine crabs (*Brachyura sp.*), greater weever (*Trachimus draco*) and lumpfish (*Cyclopterus lumpus*). For vessel B six species: Norway lobster (*Nephrops norvegicus*), golden redfish (*Sebastes marinus*), greater forkbeard (*Phycis blennoides*), long-rough dab (*Hippoglossoides platessoides*), cuttlefish (*Sepiidae sp.*) and tope shark (*Galeorhinus galeus*). For vessel C and D three species: Atlantic mackerel, edible crab and lumpfish. For vessel E five species: Norway lobster, golden redfish, lumpfish, greater forkbeard and blue ling (*Molva dypterygia*). The weight of the species never recorded in SIF ranged from 0.02% (vessels C and E) to 0.1% (vessel B).

3.2 Comparison of trips, hauls and 10 most landed species

The majority of hauls and trips were represented in both SIF and DFAD, although a third of the 14 570 species*haul combinations were missing in SIF (Tab. 3). For the reported landings, the highest completeness C_L was achieved for vessel B at around 90% on average, followed by vessel A at around 80% on average, whereas vessel C had the poorest completeness, at 69%. Overall the size class composition was similar on an aggregated level (Fig. 2) but the means differed significantly in 16 out of 39 cases when $\alpha = 0.05$ (Tab. 4). For cod, hake, haddock (*Melanogrammus aeglefinus*), lemon sole (*Microstomus kitt*), turbot (*Scophthalmus maximus*) and witch flounder (*Glyptocephalus cynoglossus*), the size classes constituted roughly the same percentage of the overall landings regardless of whether the trips had only DFAD data or had SIF too. The largest overall discrepancy was for saithe (*Pollachius virens*) where size class 3 constituted a lower percentage of the landed weight while size class 4 constituted a larger share when trips had not been recorded in SIF. However, all species had at least one size class with a significant

Table 3. Completeness of SIF when compared to the eLog (hauls and trips) and vessel landings data from DFAD for the 10 most landed species in 2015 and 2016.

	Completeness [%]									
	Vessel A		Vessel B		Vessel C		Vessel D		Vessel E	
Species	*2015*	*2016*	*2015*	*2016*	*2015*	*2016*	*2015*	*2016*	*2015*	*2016*
Wolffish	81.1	94.9	87.7	83.6	49.6	60.5	66.4	75.0	62.5	85.5
Lemon sole	88.0	77.9	77.2	100.0	58.7	67.9	41.4	54.6	63.0	86.3
Witch flounder	91.8	89.7	96.0	91.8	46.6	51.8	59.0	52.9	61.2	81.6
Hake	95.2	87.1	90.0	93.0	57.5	64.4	51.1	69.9	69.0	77.1
Turbot	79.0	82.4	93.3	76.3	58.6	68.8	16.1	76.8	64.7	83.2
Haddock	81.4	88.9	96.8	85.3	52.0	69.2	51.8	69.4	62.6	70.6
Monkfish	94.2	91.1	95.3	90.2	60.5	59.6	56.8	73.2	58.9	76.3
Cod	85.0	89.3	93.9	89.4	20.2	29.4	62.6	77.4	63.4	77.3
Saithe	68.0	94.7	91.8	90.7	21.5	55.7	60.7	70.3	55.3	74.6
Plaice	19.1	15.5	90.0	96.4	56.3	64.2	45.6	63.8	61.6	84.3
Overall species results	**78.3**	**81.2**	**91.2**	**89.0**	**48.2**	**59.2**	**51.2**	**68.3**	**62.2**	**79.7**
Fishing trips, number in SIF	**39**	**67**	**35**	**37**	**83**	**88**	**59**	**53**	**42**	**48**
Fishing trips, completeness [%]	**100.0**	**100.0**	**89.7**	**78.7**	**98.8**	**100.0**	**100.0**	**98.1**	**95.5**	**100.0**
Hauls, completeness [%]	**89.8**	**82.6**	**92.3**	**74.8**	**82.6**	**71.5**	**61.6**	**79.0**	**65.3**	**80.0**

difference in percentwise composition. Conversely, all species also had at least one size class where no significant difference was found. Additionally, the standard deviation was large for all species and size classes, meaning that large variation in size composition occur between trips.

Log-transformation of landings recorded in SIF and DFAD was necessary to assume normal distribution (Fig. 3). A scatterplot and a linear model fit was made for the size classes of the 10 investigated species of each vessel at trip level (Fig. 4 and Tab. 5). Saithe, turbot, witch flounder, wolffish (*Anarchichas spp.*) and monkfish (*Lophius spp.*) had R^2-values and a scatterplot close to a 1:1 ratio between SIF and DFAD by trip for most vessels. However, monkfish was not sorted into size classes on vessel A when sea-packed, and vessel E had several trips with a poor fit for the medium size classes of saithe as well as some trips with a poor fit for the largest size class of wolffish. Correlations were also generally high for hake and lemon sole but vessel D had several trips where the larger size classes of these two species had a poor fit. Vessel A also had some trips with a poor fit for lemon sole, and this species was rarely landed for vessel B. Haddock had high R^2-values as well but not for all years and all vessels, where especially vessel B and D in 2016 had a poor fit. Cod had R^2-values and a scatterplot with a good agreement between SIF and DFAD for vessel B, but not for the rest of the vessels. For plaice (*Pleuronectes platessa*) the scatterplot and R^2-values were poor for most vessels. Interestingly, some occurrences of more landings in weight in SIF than DFAD appeared, mainly for witch flounder, which in theory should not be possible, since the summing of all SIF data should also be found in the total recorded landings for any given trip. Presenting this to the fishers revealed two reasons; (1) small mismatches are inevitable, as the fishery auctions, from where the landings data in DFAD are derived, only record landings in total kilograms, whereas the sea-packing equipment uses scales with dynamic motion compensation and relay data with two decimals. (2) Larger mismatches could be an artefact in the SIF system. If a crate is labelled wrongfully, e.g. by recording the wrong size class or species, a new label must be made. This in turn will be recorded as a new entry in SIF and the fishers cannot delete the old entry, meaning that the same crate will count twice in SIF.

Extension of the model to include the effect of year, vessel and size class revealed that each of these factors could have a significant effect among the species (Tab. 6). The effect of year was significant for cod, hake and lemon sole. Vessel effect was significant for all species, except haddock and turbot and the effect of size class was significant for all species, except witch flounder. The log-transformed landings in DFAD had a significant effect and the largest sum of squares and F-value for all species.

3.3 Spatial distribution of hauls compared to EM data

The exclusion criteria to filter for unrealistic haul lengths and towing speeds in SIF led to the exclusion of respectively 91 and 71 hauls for the two EM vessels, corresponding to 6.33% and 7.67% of recorded hauls. Overlay maps for positions according to EM GPS data and according to SIF in 2015 and 2016 are presented in Figure 5. Visually, most areas had overlap between SIF and EM but in 2015, the difference between positional data in SIF and EM was statistically significant (Tab. 7). An area at roughly 59° N and 0.5° W was visually identified where fishing took place according to EM but no hauls have been recorded in SIF, neither in 2015 nor in 2016.

4 Discussion

The SIF dataset possess information not available in the currently used commercial fisheries data. That cover direct observations on size distributions at the haul level instead of merely at the trip level. The completeness of SIF compared to

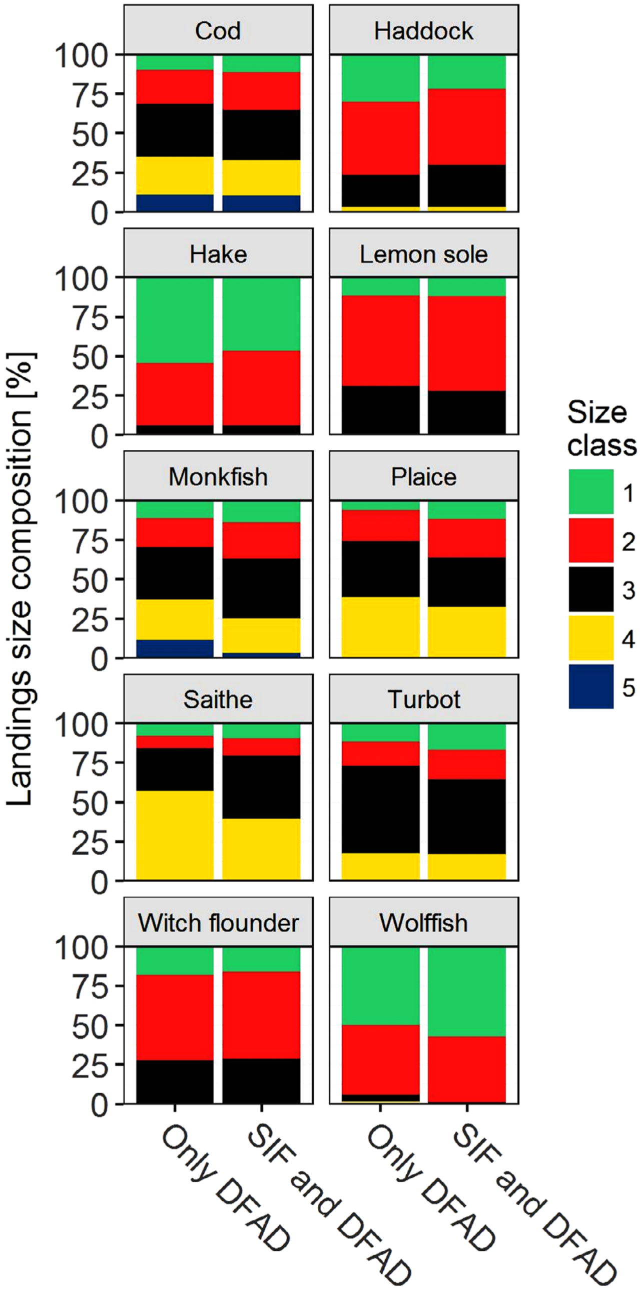

Fig. 2. Landings' size composition in percent stratified on trips with only DFAD data and trips with both DFAD and SIF data. Size class 1 are the largest specimens.

DFAD shows overall a good match, albeit not perfect. Although all five vessels landed a few species that were never sea-packed and, consequently, present in DFAD but not in SIF, these species only constituted a minor fraction of the vessels' total landings. Thus, they were non-target species for the vessels. According to the fishers, vessels engaged in sea-packing may choose not to sea-pack a species if it is not considered worth the effort of sea-packing during the catch processing. Norway lobster is an example of a potential target species that is not necessarily sea-packed. This is because as the added value is not considered to be large enough, which is also the case for several flatfish species.

Fishing trips and hauls recorded in the eLog were overall well represented in SIF. No discards were recorded in SIF, which is likely because the legal purpose of the dataset is for traceability requirements of the landings.

Several trips had records of landings for one or more of the 10 investigated species in DFAD but no records of the species in SIF. A reason for this may be the loss of data when merging DFAD and SIF, because there are no unique haul and trip IDs shared between SIF and DFAD. Therefore, the common identifier used to merge SIF and DFAD was the landings date, which can be inferred from SIF and is recorded in the DFAD data. Mismatch may also be due to lack of vessel storage capacity to pack all their landings in crates at-sea. Because it takes up more storage room to sea-pack landings there is a trade-off between continuing to fish after the storage capacity for sea-packing is reached. On the one hand, sea-packing should give a higher quality and thereby higher price for the landings (Frederiksen and Olsen, 1997; Frederiksen et al., 2002). On the other hand, the cost of steaming between fishing grounds and port may make it more profitable to continue fishing, store landings in larger bulks, and land a larger amount of unsorted fish, which will give a higher total revenue. The choice between one and the other is likely to be influenced by several factors. These include among others as the amount of remaining quota, the expected value of the landings already in storage, how far into the expected duration of the fishing trip a haul takes place, and the weather conditions. Accordingly, there may not necessarily be consistency between fishing trips as to whether a species is sea-packed or not. The fact that plaice is the species where SIF records are poorest supports this, as plaice is a relatively low value species in this context. Conversely, it is likely that species with a high profit gained from sea-packing will have the best agreement between DFAD and SIF records. Monkfish has good agreement for most vessels, which supports the above perspective as monkfish has a relatively high value. The model extension to include the effect of year, vessel, and size class for each species did not reveal which factors specifically and significantly influence the choice of sea-packing or not. The model output show that factors other than year, vessel, and size class significantly influence the lack of a perfect fit between SIF and DFAD records. As stated above, external factors may well heavily influence the choice. This include factors that may vary substantially such as fish price. Furthermore, due to the Danish Individual Vessel Quota system, it is difficult to specify the remaining quota during a year, which may also influence the choice. We, nonetheless, consider it to be beyond the scope of this study to further analyse these factors here. Future studies on the frequency of storage limitations, possible correlation between expected fish prices and sea-packing, or cost-benefit analysis of the added workload at-sea compared to the potential gain from sea-packing could shed further light on the underlying reasons and key driving factors behind the frequency of trips with landings recorded in DFAD while lacking in SIF. The potential bias created by lack of SIF records for certain trips seems limited, though. Overall, there are only small differences in the percentwise size composition in the landings for the DFAD dataset when looking at trips where SIF data was available compared to trips with no SIF data available. However, statistical test output of the percentwise composition suggest large variation among trips. As a whole,

Table 4. Mean and standard deviation in percentage of size classes as well as *p*-value from Wilcoxon rank-sum test. Comparison is done solely using DFAD data between trips where only DFAD data exist and trips where both SIF and DFAD data exist. *Vessel A is not included for monkfish as the vessel do not sea-pack monkfish.

Species	Size class	*p*-value	Mean percent ± SD [%] only DFAD	Mean percent ± SD [%] SIF and DFAD
Cod	1	0.875	22.7 ± 28.8	15.3 ± 14.1
	2	0.276	26.3 ± 17.6	25.6 ± 12.3
	3	0.002	35.8 ± 17.0	29.9 ± 15.1
	4	0.006	28.1 ± 19.5	22.1 ± 11.5
	5	0.167	20.1 ± 27.6	12.6 ± 12.8
Hake	1	0.004	36.6 ± 25.9	38.2 ± 17.8
	2	0.999	54.4 ± 25.6	54.2 ± 20.1
	3	0.004	34.2 ± 34.2	14.4 ± 14.1
	4	0.080	33.4 ± 34.5	10.1 ± 11.7
Plaice	1	0.007	32.1 ± 29.1	24.0 ± 25.4
	2	0.520	29.1 ± 16.2	28.6 ± 12.6
	3	0.178	29.1 ± 18.0	30.4 ± 13.2
	4	0.821	31.6 ± 26.7	27.8 ± 17.5
Haddock	1	0.006	43.8 ± 24.2	35.7 ± 20.9
	2	0.006	52.9 ± 24.5	51.4 ± 18.4
	3	0.082	30.7 ± 27.4	26.3 ± 15.7
	4	0.707	34.6 ± 40.0	9.0 ± 6.3
Saithe	1	0.056	30.9 ± 31.4	23.7 ± 28.6
	2	< 0.001	35.6 ± 33.9	16.6 ± 17.1
	3	0.234	40.6 ± 27.7	42.0 ± 22.7
	4	0.049	55.8 ± 27.5	46.8 ± 27.3
Lemon sole	1	0.072	24.1 ± 23.8	16.3 ± 12.6
	2	0.595	60.7 ± 16.4	60.3 ± 14.2
	3	0.038	34.5 ± 22.4	28.4 ± 13.9
*Monkfish**	1	0.138	23.1 ± 25.8	15.0 ± 10.9
	2	0.186	25.0 ± 14.4	21.9 ± 10.0
	3	0.807	37.2 ± 15.7	36.9 ± 11.6
	4	0.004	34.9 ± 22.6	27.0 ± 14.1
	5	< 0.001	27.1 ± 33.7	10.1 ± 14.5
Turbot	1	0.820	36.2 ± 32.6	35.1 ± 30.9
	2	0.083	34.6 ± 27.8	27.5 ± 20.4
	3	0.401	51.9 ± 24.9	48.5 ± 22.3
	4	0.013	30.8 ± 26.5	20.9 ± 15.6
Witch flounder	1	0.889	30.8 ± 24.5	28.2 ± 18.3
	2	0.012	67.4 ± 24.4	59.9 ± 19.6
	3	0.331	35.9 ± 27.3	28.7 ± 15.7
Wolffish	1	0.940	52.7 ± 24.1	52.2 ± 22.6
	2	< 0.001	70.0 ± 28.7	58.4 ± 26.6
	3	< 0.001	50.6 ± 44.9	6.3 ± 6.3

the investigations and tests comparing SIF and DFAD revealed that a consistent bias in SIF records seems unlikely. Lack of entries in SIF varies between vessels, years, species and possibly size classes, although fishers have stated that they either do not sea-pack a species or sea-pack all retained specimens at the hauls where they sea-pack. In light of this, SIF should not be viewed as a full record but rather as a subsample of the landings with higher resolution for certain species. Due to the species-to-species variation in reliability in SIF, studies utilizing SIF data should verify the completeness of the

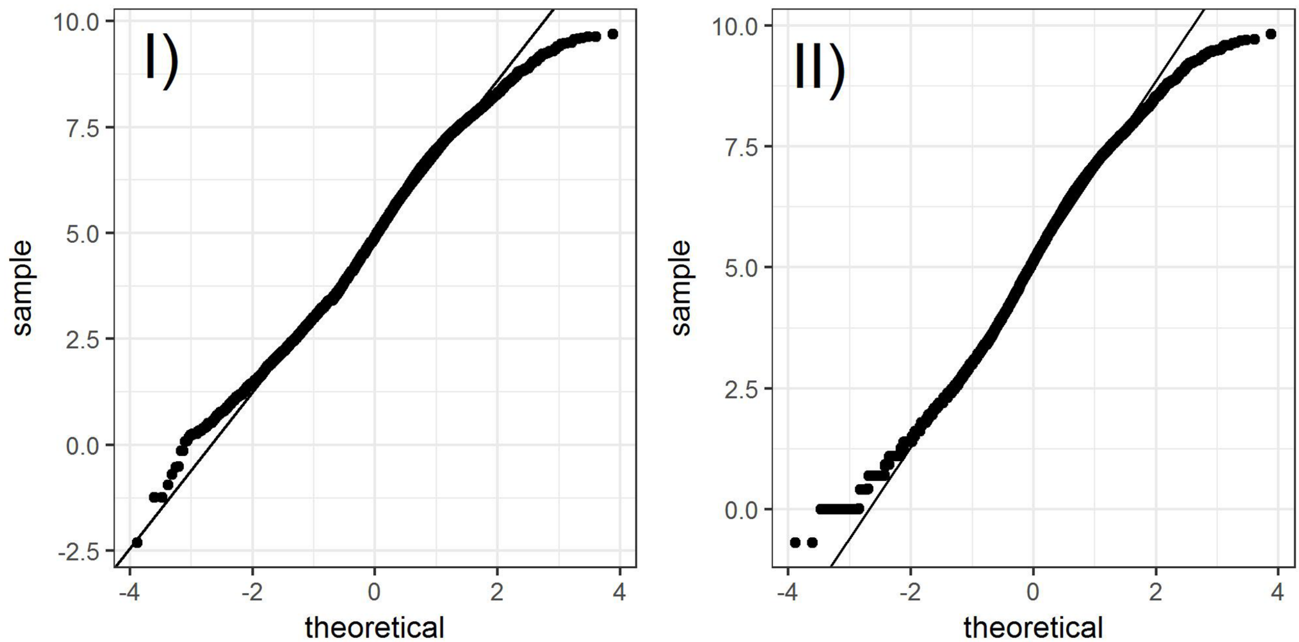

Fig. 3. QQ-plot for (I) log-transformed landings recorded in SIF. (II) log-transformed landings recorded in DFAD.

specific SIF data available for those species, which are to be investigated, prior to any further analysis.

4.1 Spatial data

Overall, there is a good spatial overlap between the SIF and EM datasets. However, some gaps in spatial coverage occur, and a statistically significant difference between mid-points of hauls was found for 2015. Several reasons can explain the discrepancy. First, hauls recorded in SIF with unrealistic duration and towing speeds were excluded which inevitably creates gaps for SIF compared to EM. Second, positional data in SIF is exported from the eLog. Although the eLog software allow for real-time entries of the vessel's position, the skipper may postpone entries of haul data, including fishing time and position, as long as the data has been entered prior to the mandatory deadline of data transmission (once every 24 h). Therefore, a certain mismatch could be caused by human errors if positional data is entered manually in the eLog. Third, there is an inherent error in plotting a haul as a simple straight line from haul start to end. Adjustments in vessels' course and drag will mean that towing paths are not conducted in straight lines in the real world, which can cause mismatch when assuming a straight line between start and end position of the haul. Fourth, some gaps may come from fishers testing an area for fish. If the catch in this area is poor, then no sea-packing will occur, meaning that no haul is recorded in SIF, but because a fishing activity was recorded in EM, the haul will appear in the EM data. This could explain the mismatch in an area around 59° N and 0.5° W. Fifth, the spatial resolution of the data used for the statistical test will influence the outcome of the test of means. Finally, breakdowns have happened in the GPS equipment during the EM trial, meaning that it is possible for hauls to have taken place and be present in SIF without being recorded in EM.

4.2 Using SIF data

When taking the differences in data between DFAD and SIF into account, it is clear that the quality of the SIF data has to be scrutinized at the vessel and species level before it can be utilized for scientific and management purposes. Spatial and temporal entries in SIF seem valid, but due to inaccurate reporting, it is necessary to filter out hauls where spatial or temporal records are unrealistic. This can be done by setting up exclusion criteria and filtering by these. Prior to in depth analysis of species distributions it is necessary to validate the species records in SIF for the individual year, vessel, species, and size class. The agreement between DFAD and SIF can vary substantially. The discrepancies originating from incorrect crate labelling are more difficult to remove. It is a very species and vessel specific issue and therefore only relate to analysis for these specific species, e.g. witch flounder. The simplest approach is to exclude the records from the problematic vessel and/or species, depending on the analysis. The more cumbersome solution is to identify the trips where incorrect labelling has happened, as can be done for the trips where SIF do not contain the majority of landings of a species. By identifying the vessel, species and size class, one can find the corresponding landings in DFAD and SIF and subset for these. Then, using the landings date, the corresponding hauls for the specific fishing trip can be removed from the dataset.

Based on talks with sea-packing fishers, species are generally either sea-packed at the haul level or not at all. Mismatch between SIF and DFAD at the trip level should be due to hauls where species where not sea-packed rather than hauls where a fraction of a species was sea-packed. However, the effect of size class in the extended model does not fully support this statement.

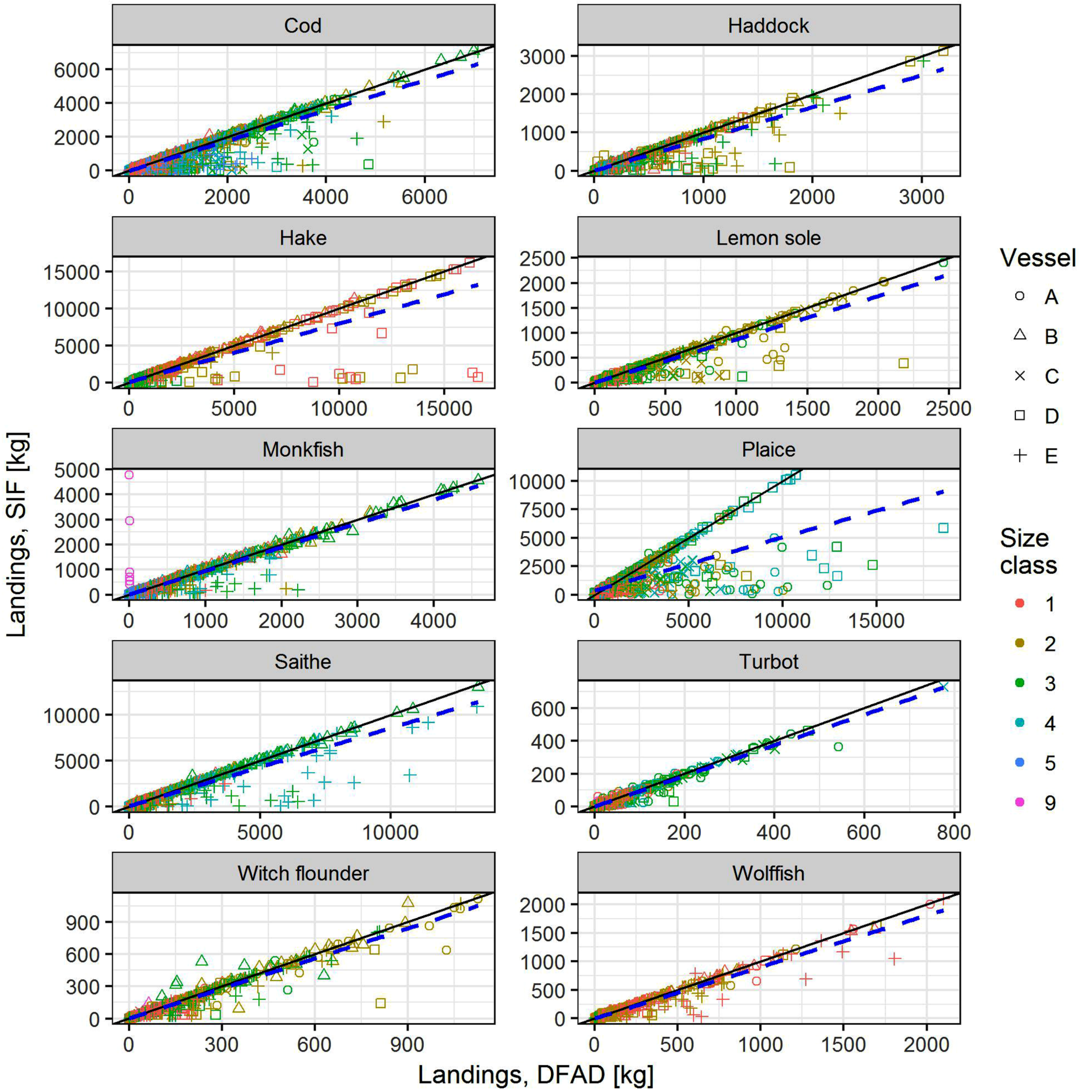

Fig. 4. Landings per trip according to DFAD and SIF for the 10 most landed species in 2015 and 2016 by species and commercial size class. Points: the aggregated weight of the species and size class for a fishing trip. The *x*-axis represent the weight according to DFAD, the *y*-axis represent the weight according to SIF. Blue dashed line: linear model fit between DFAD and SIF. Black line: the 1:1 ratio between DFAD and SIF. Size class 9 is unsorted.

4.3 Possible applications

There are clear limitations regarding the usefulness of SIF owing to the facts that (i) the future of SIF is uncertain due to funding issues, (ii) the majority of Danish fishing vessels do not use it, and (iii) vessels can refuse to share SIF data. Furthermore, several vessels with sea-packing do not complete the entries into SIF in a manner that allow for better spatial resolution than DFAD. The relatively short time coverage of SIF further limits its use. Nevertheless, SIF have several benefits: SIF data is already collected and is therefore a free data source, which only requires the time spent on access permission and adjustment of a web scraper to collect. SIF does not serve as a direct control measure but is used for commercial purposes and to fulfil traceability requirements, whereby there should be little if any incentive to tamper with the system. This study serves, therefore, as a proof of concept that it is possible to obtain precise size distribution from fisheries data at the haul level, even though it is not a legal requirement. Indeed, the fisheries control in Greenland already

Table 5. R^2 and degrees of freedom for linear model fit of landings in SIF and DFAD for the 10 most landed species in 2015 and 2016. SIF data has been aggregated to trip level in order to make the comparison possible with DFAD and comparison is done solely for trips where both SIF and DFAD have records.

	Vessel A				Vessel B				Vessel C				Vessel D				Vessel E			
	2015		2016		2015		2016		2015		2016		2015		2016		2015		2016	
Species	df	R^2	df	R^2	df	R^2	df	R^2	df	R^2	df	R^2	df	R^2	df	R^2	df	R^2	df	R^2
Wolffish	38	0.997	82	0.993	35	0.999	59	0.885	40	0.793	65	0.952	46	0.946	60	0.953	62	0.914	81	0.975
Lemon sole	88	0.936	156	0.978	5	0.574	8	0.859	146	0.836	155	0.985	56	0.981	100	0.890	65	0.944	88	0.985
Witch flounder	55	0.966	84	0.975	33	0.986	12	0.805	28	0.952	69	0.999	21	0.995	83	0.876	82	0.841	105	0.912
Hake	38	0.979	39	0.985	37	0.987	65	0.997	77	0.747	77	0.981	53	0.701	71	0.777	94	0.775	131	0.963
Turbot	117	0.946	228	0.921	27	0.899	31	0.732	120	0.940	165	0.949	30	0.988	79	0.940	40	0.919	63	0.983
Haddock	40	0.972	89	0.855	50	0.991	26	0.704	95	0.880	111	0.978	72	0.813	95	0.552	98	0.831	139	0.857
Monkfish	NA	NA	NA	NA	69	0.997	121	0.996	139	0.933	191	0.886	75	0.922	161	0.899	152	0.749	181	0.880
Cod	122	0.776	212	0.981	56	0.994	109	0.998	227	0.703	260	0.713	125	0.702	169	0.743	160	0.607	182	0.803
Saithe	22	0.908	27	0.994	56	0.999	98	0.998	13	0.737	63	0.963	61	0.904	40	0.853	123	0.731	146	0.918
Plaice	70	0.524	124	0.472	9	0.825	5	0.779	201	0.673	207	0.763	49	0.889	104	0.889	81	0.897	94	0.980

Table 6. ANCOVA output for the effect of year, vessel and size class as well as remaining effect of log-transformed landings from DFAD and residuals.

Species	Term	df	Sum of squares	*F*-value	*p*-value
Cod	log(DFAD)	1	65411.5	$1.701 * 10^5$	<0.001
	Size class	5	10.6	5.490	<0.001
	Vessel	4	35.5	23.083	<0.001
	Year	1	2.1	5.441	0.019
	Residuals	1902	731.5		
Hake	log(DFAD)	1	26669.1	91823.644	<0.001
	Size class	5	2.3	1.591	<0.001
	Vessel	4	12.9	11.144	<0.001
	Year	1	1.8	6.207	<0.001
	Residuals	777	225.7		
Plaice	log(DFAD)	1	41100.6	86700.459	<0.001
	Size class	5	18.6	7.831	<0.001
	Vessel	4	14.9	7.874	<0.001
	Year	1	1.7	3.581	0.059
	Residuals	1019	483.1		
Haddock	log(DFAD)	1	20513.9	64726.260	<0.001
	Size class	5	1.5	4.579	<0.001
	Vessel	4	0.4	1.398	0.233
	Year	1	0.1	0.258	0.611
	Residuals	863	273.5		
Saithe	log(DFAD)	1	28087.3	117068.100	<0.001
	Size class	5	92.5	0.771	<0.001
	Vessel	4	15.4	16.000	<0.001
	Year	1	4.8	20.000	0.571
	Residuals	736	176.6		
Lemon sole	log(DFAD)	1	20182.6	183262.301	<0.001
	Size class	4	3.7	8.292	<0.001
	Vessel	4	2.1	4.694	<0.001
	Year	1	1.5	13.782	<0.001

Table 6. (continued).

Species	Term	df	Sum of squares	*F*-value	*p*-value
	Residuals	905	99.7		
Monkfish	log(DFAD)	1	29525.7	145400.713	<0.001
	Size class	6	64.4	52.859	<0.001
	Vessel	4	70.3	86.536	<0.001
	Year	1	0.1	0.356	0.551
	Residuals	1208	245.3		
Turbot	log(DFAD)	1	10539.5	108462.110	<0.001
	Size class	5	3.8	7.881	<0.001
	Vessel	4	0.8	2.145	0.073
	Year	1	0.1	0.082	0.774
	Residuals	930	90.4		
Witch flounder	log(DFAD)	1	12335.2	110089.201	<0.001
	Size class	4	1.0	2.213	0.066
	Vessel	4	2.2	4.965	<0.001
	Year	1	0.1	0.718	0.397
	Residuals	626	70.1		
Wolffish	log(DFAD)	1	10820.2	93123.94261	<0.001
	Size class	4	2.3	4.852	<0.001
	Vessel	4	1.9	4.182	0.002
	Year	1	0.2	1.464	0.228
	Residuals	595	69.1		

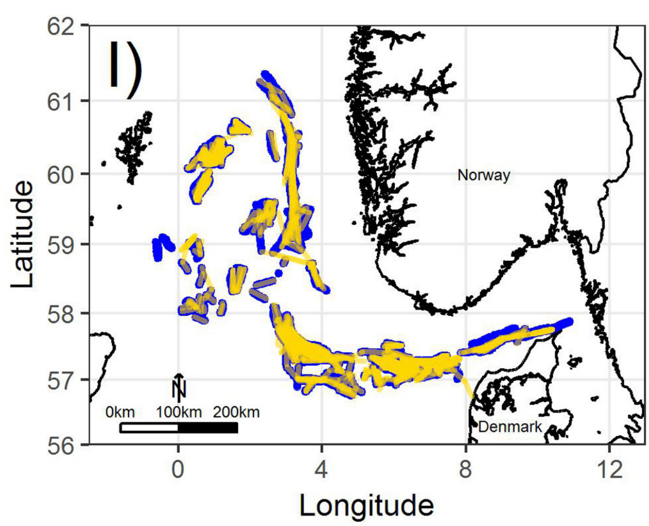

Fig. 5. Fishing activity overlap between EM and SIF for two vessels. (I) 2015. (II) 2016. Blue points: Fishing activity recorded by EM GPS sensors (1-minute interval). Yellow lines: Hauls according to SIF. The EM trial did not cover the Baltic Sea and the maps do therefore not include hauls in this area.

Table 7. Mean latitude and longitude as well as *p*-value from Wilcoxon rank-sum test for all hauls recorded in SIF and EM during 2015 and 2016. Two vessels had records in both datasets. Due to confidentiality agreements, the number of hauls cannot be revealed, however it exceeded 1000 observations in both years.

Year	Mean latitude, SIF	Mean latitude, EM	*p*-value	Mean longitude, SIF	Mean longitude, EM	*p*-value
2015	58.16 °N	58.26 °N	<0.001	4.72 °E	4.34 °E	<0.001
2016	58.17 °N	58.27 °N	0.174	4.71 °E	4.34 °E	0.701

requires vessels above 75 GRT to include the size distribution of the landings at the haul level (Greenland's Autonomy, 2010). Although the number of sea-packing vessels is low in Denmark, the landed volume from sea-packing vessels is large and the activity coverage is extensive. The five Danish vessels investigated in this study have SIF data from 258 trips in 2015 and 293 trips in 2016. In 2015 and 2016, the entire Danish observer programme covered a total of 224 and 262 trips respectively. When SIF and observer data overlap, SIF could also be used to investigate potential behavioural aspects of observer presence. Because fishers may refuse to take observers on-board, there is a risk of a bias in the observer data relative to the reason for not wanting observers. Likewise, fishers may adapt their fishing behaviour while carrying observers, either intentionally or unintentionally, which may also cause a bias in observer data. While sharing SIF data with scientist or fisheries managers is purely voluntary, there is an economic incentive to conduct sea-packing as costs are reduced (Frederiksen and Olsen, 1997; Frederiksen et al., 2002) and vessels are liable to the fish auctions for correct labelling of sea-packed landings. Therefore, the risk of fishers adapting fishing behaviour is less likely for SIF. Investigations with SIF data could enhance the knowledge on spatial explicit fish distributions, for instance by mapping areas with a larger share of juveniles for certain species, whereby fishers may improve their spatial selectivity. Especially monkfish and wolffish could be of interest for analysis utilizing the size class information in SIF as these species are data poor and have some of the best records in SIF for the investigated species.

Based on the presented results, the next planned step in utilization of SIF data is to compare the spatial and temporal distribution of size classes for species well represented in SIF data, to that of DFAD and VMS-logbook coupled data. This will allow for testing the validity of the homogeneous reallocation of size classes, as well as showing the importance of having the size composition at the haul level.

5 Conclusion

SIF provides new, relatively reliable data on the size composition of important commercial fish species with the same or higher resolution than what is available in traditional fisheries data. However, the quantity, quality and reliability vary between vessels and species. Although SIF has high coverage and detailed landings and spatio-temporal information, the dataset has limited coverage in the number of vessels. If the SIF database is maintained and SIF data continuously collected, we believe SIF could provide additional knowledge on detailed spatial patterns of fishing effort and commercial fish species and size distributions. Because SIF provide direct observations at the haul level it could be used for analysis at a vessel or métier specific level, for instance on catchability, spatial selectivity, seasonal patterns or to compare and verify outcomes of spatial fishery evaluation models as evaluated in Nielsen et al. (2018). A fleet-wide application or stock assessment usage would require an expansion of the vessel coverage and better accessibility to SIF data. It is our hope that this study may serve as a case study to highlight the possibilities that exist in enhancement of commercial fisheries data available to science.

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Paper III - More data for the money: Improvements in design and cost efficiency of electronic monitoring in the Danish cod catch quota management trial

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More data for the money: Improvements in design and cost efficiency of electronic monitoring in the Danish cod catch quota management trial

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A R T I C L E I N F O

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A B S T R A C T

Electronic Monitoring (EM) with video is a tool often mentioned to ensure compliance with fishing regulations while vessels are at sea. Since 2008, several trials have been conducted in the European Union on the use of EM. One of the largest and longest running European trials was the 2010–2016 Cod Catch Quota Management trial (CCQM) in Denmark. This paper reviews the methods and experiences gained from this trial, with focus on the last two years where criteria for video audits were expanded and major technical developments took place. The cost-effectiveness and potential of EM for compliance, management and scientific purposes is discussed. The present study demonstrates that EM is capable of high precision detection of non-compliance with a discard ban and that developments in the transmission of EM data allowed for a smoother and more reliable Monitoring, Control and Surveillance (MCS) system. Although further developments are needed, especially within the field of automated image analysis, we conclude that EM is one of the few feasible tools where fisheries information and compliance can be ensured under a Landing Obligation.

1. Introduction

The use of Electronic Monitoring (EM) with video has been tested in a number of fisheries worldwide for more than a decade (van Helmond et al., in review). In certain Canadian fisheries, vessels are required to either carry EM with video or have on-board observers (Stanley et al., 2011) and New Zealand is currently set to introduce mandatory video installation as part of the country's fisheries management (Hersoug, 2018; Reddy, 2017). Several European countries conducted trials with EM from 2008 and onward (van Helmond et al., in review). The introduction of a discard ban in the European Union (EU), known as the Landing Obligation (LO) has increased the relevance of EM in an EU context. According to article 15 of the 2013 Common Fisheries Policy (CFP) of the EU, Member States are obliged to "ensure detailed and accurate documentation of all fishing trips". Observers and EM are stated as specific means for this while the article allows for other, non-specified measures as long as Member States respect the principle of efficiency and proportionality (EU, 2013). Danish experiences with EM began in 2008 with a one year pilot project run by the National Institute of Aquatic Resources at the Technical University of Denmark (DTU Aqua) with the objectives of testing the use of EM on board trawlers, gillnetters and Danish seiners (Dalskov and Kindt-Larsen, 2009). The trial focused on estimating cod (*Gadus morhua*) discards from video and investigating whether fishers would be able to record them correctly. Following the promising results of this trial, a second trial known as the Cod Catch Quota Management trial (CCQM) began in April 2010. The CCQM focused on the control and management potential of EM and was run as a collaboration between the Danish Fisheries Agency and DTU Aqua (Ulrich et al., 2015). After 2014, the CCQM underwent several changes. In 2015 and 2016 the trial was run solely by the Danish Fisheries Agency and its purpose shifted to focus more on developments for species recognition, camera quality and length measurements (Bergsson et al., 2017; Bergsson and Plet-Hansen, 2016). The last CCQM data collection in 2016 concluded almost seven years of catch quota management verified by EM in Denmark. In the present article, we present the technical developments and lessons learned from the CCQM. A few studies have already been published on this trial, including studies on the behavioral effect of EM with video on Danish vessels (Kindt-Larsen et al., 2011; Ulrich et al., 2013), a first analysis on the trial outcomes over the period 2010–2014 (Ulrich et al., 2015), and a study on fishers' and fisheries inspectors' views (Plet-Hansen et al., 2017). The present study focuses thus on the most recent developments and experiences of the CCQM trial in 2015 and 2016. The objectives are to analyze the discards patterns but also to describe the evolution of technology and data handling processes, and document the best practice experiences gained that improved the reliability and efficiency of

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the EM system and reduced the costs. This knowledge is useful information for future EM programs, as technical specifications are usually only little described in EM published literature, being often hidden in unpublished reports.

2. Material and methods

2.1. Area and participants

In 2010 and 2011, the Danish CCQM trial covered fisheries conducted in the North Sea, Skagerrak and the Baltic Sea (Dalskov et al., 2012, 2011). After 2011, the trial was geographically limited to monitor vessel operations in the North Sea and Skagerrak (Bergsson et al., 2017; Bergsson and Plet-Hansen, 2016; Plet-Hansen et al., 2015). Incentives for participation were exemption from days-at-sea regulations and a cod quota uplift of 30% for the first 100 tonnes of cod TAC and a 20% increase of any cod TAC above 100 tonnes held by the vessel at the beginning of the year. The Danish fishery for demersal species like cod has been governed by a Vessel Quota Share (VQS) system since 2007 (Andersen et al., 2010). It was therefore specified that any additional acquiring of cod quota throughout the year via the VQS-system would not be subject to the quota uplift for trial participation. The reasoning behind the days-at-sea exemption and quota uplift were that the Catch Quota was targeted at cod and the uplift was set to reflect the overall discard estimate for the Danish fishing fleet (Dalskov et al., 2012, 2011; Ulrich et al., 2015). Participating skippers were required to fill in their electronic logbook (eLog) on a haul-by-haul basis, including position, date and time for setting and hauling of gear, the landings and the discards. The number of participating vessels in the trial varied from 7 in 2010 up to 24 participants in 2012. In 2015 and 2016, 13 and 12 vessels participated in the trial, respectively. A full list of participating vessels is available in the supplementary Table A1.

2.2. EM technology and data flow

Until 2014, the EM system provided by Archipelago Marine Research Ltd. was used. The system consisted of a GPS, hydraulic pressure and drum rotation sensors as well as video cameras. Recorded data was stored on a control box hard drive. Data transmission was done manually by fisheries inspectors who replaced the vessels' hard drives while in port and sent the collected hard drives by postal order to the Danish Fisheries Agency's head office (Ulrich et al., 2015). From September 2014, the vessels' EM systems were replaced with the Anchor Lab K/S Black Box Video system (Anchor Lab K/S, 2017). Replacements were carried out when planned fishing trips or maintenance tasks kept the participating vessels in port for longer durations (more than one week). The new system acquired vessel positions using a GPS antenna on the wheelhouse where antennas for data transmission via GSM, 3 G, 4 G, Wi-Fi or satellite were placed as well. Drum rotation sensors mounted on winches provided data on setting and hauling of gear. In 2015, all video footage was recorded using 2 megapixel (MP) wide-angle lens cameras. In 2016, all cameras recording the vessels discard chute were replaced by 3 M P and 5 M P square-lens cameras to get better imagery for length measurements of individual fish. The standard number of cameras was four but the EM system handled six cameras on some vessels in both 2015 and 2016. Recorded data from cameras, GPS and rotation sensors was stored on two on-board 1 TB hard drives. Data transmission via GSM, 3 G, 4 G or Wi-Fi to the Danish Fisheries Agency took place while vessels were in port vicinity. A two month trial transmitting sensor data twice a day while at sea via satellite connection was tested as a proof of concept and proved to be successful. In practice however, data transmission was done online while vessels were in port. During 2015 and the first half of 2016, the internet provider allowed for transfer rates fluctuating between 5 megabit per second (Mbit/s) and 90 Mbit/s. The transfer rates mainly varied between 10–20 Mbit/s depending on location of vessel within the port. In the second half of 2016, data load transmission was improved by changing the compression standard for video records from H.264 to H.265 for some cameras whereby video data could be compressed by at least 15% without loss of image quality. Additionally, the internet provider in the main harbor for participating vessels (Hanstholm) was also changed. The new internet provider made it possible to achieve standard transfer rates of 50–90 Mbits/s.

2.3. Video audit software, hardware and procedures

During 2010 to 2014, audited videos would receive a comment if something out of the ordinary was seen. This included comments on possible errors or malfunctions, such as system breakdowns, unclean camera lenses etc. If no comment was made, the video was of sufficient quality. From July 2015, a grade system of video quality was introduced, where low grades had to be accompanied by a comment from the video auditor on the reason(s) for the given grade. Until 2015, video auditors divided discards into two categories for registration: Cod and Other. In practice, this meant that only cod discards were well documented, because the term "Other" could cover a large variety of species and only provided an estimate of the total discard of fish from the given vessel. Discard estimates were entered into a spreadsheet as mass per haul in kilograms. Before July 2014, mass estimation was based on the empirical knowledge that video auditors gained. That is, auditors would estimate the length of a discarded fish based on their knowledge of the field of view in the video and of visible fixed structures for the specific vessel. They would then estimate the mass of the discarded fish based on their assessment of its length and condition. If in doubt, auditors could refer to a mass-length relationship table. All lengths were based on the auditors own estimate, since no software measuring tools were available. From July 2014 this was changed by 1) the introduction of a grid overlay and 2) alteration of audit procedures and recorded species.

2.4. Introduction of a grid overlay

During 2014, re-measurements of conveyor belts and adjacent structures on the vessels were conducted. This knowledge of the dimensions of several objects within the field of view made it possible to develop and calibrate a grid overlay system. The first version of the grid overlay was launched for video audit in July 2014 and was a standalone program that would display a transparent grid which could be placed on top of the video footage from the EMI software (Fig. 1). After the change in EM provider and an initial transition period, the grid program was incorporated as part of the Black Box Analyzer and improved by adding a measuring tool to the analysis software (Fig. 1).

2.5. Alteration of audit procedures and recorded species

In conjunction with the implementation of the grid overlay, the video audit procedures were adapted continuously leading to four different audit methods applied over the full CCQM duration (Table 1). Method 1 with manual entry of discard mass estimates into a spreadsheet was replaced with a custom interface with an integrated database (Method 2). The database was connected to a custom made acquisitioning software where the video auditors could directly enter length estimates at 5 cm length intervals. Length estimates would automatically be converted to mass for each recorded fish based on the length-mass relationship for the species, and the estimated discard mass would be relayed back to the database together with haul info. The discard category "Other" was discontinued because the data was somewhat unusable and focus was moved to discards of cod, saithe (*Pollachius virens*), whiting (*Merlangius merlangus*) and haddock (*Melanogrammus aeglefinus*). In October 2015, hake (*Merluccius merluccius*) was included in the audit too (Method 3). All other discards were no longer registered. This meant a change in the type of recorded data, from focusing on a high data quality for discards of one species and low

Fig. 1. Left: Example of image for video audit with the first version of the grid overlay. Grid scale set on this example was a 10 cm interval. Right: Example of image for video audit with the final grid overlay and measuring line integrated in the Black Box Analyzer. The image shows the measuring line on a monkfish (*Lophius* spp.) of 65.7 cm in length in a curved position. The scale set for this grid overlay was 5 cm interval.

data quality but total discard mass for all other commercial species, to high data quality for discards of 4 (later 5) species and no data for all other discards. These changes also led to a change in the computer hardware used for discard recordings, detailed elsewhere (Bergsson et al., 2017; Bergsson and Plet-Hansen, 2016). From July 2016, Method 4 was introduced, where a Shuttle Pro V2 Contour Design was used to navigate in the video footage (e.g. fast forward or replaying footage) together with a Logitech® G502 mouse. EM data would be transmitted to the Danish Fisheries Agency's webservice. The project manager would ensure merger of hauls in the EM system and reported in the eLog for verification of compliance. Random hauls would be selected for audit, whereby these would appear for video auditors in the custom interface. Auditors would not be able to view eLog data for a haul until the haul audit had been completed. Audit for selected hauls would cover all discards of cod, hake, haddock, saithe and whiting registered and the length of each discarded fish was estimated by placing the measuring line in the Black Box Analyzer manually. The measuring line could be bent when fish were lying in a curved position (Fig. 1). The length estimate would be recorded directly in the data acquisitioning software at a 0.1 cm scale and used for the length-mass relationship. Additionally, a snip of the video sequence containing the discarded fish was taken and saved automatically when measuring the fish. Thus, with Method 4 every single discard of cod, whiting, saithe, hake and haddock would be recorded with an ID-marker, video stamp, length measurement, mass estimate and a picture of the fish. This was done to enhance the integrity of the audit as it made future verification of species and size estimates easy. For further overview of the gameboard, gamer mouse and Shuttle Pro used for video audit we refer to Bergsson et al., 2017. It is important to remember that all improvements in discard assessment were based on the length measurements and that the mass of the discards would be derived from the length-mass relationship of each species. Variation in fish mass due to condition was not included such that data from the CCQM is more robust with respect to length and number records than with respect to mass records.

2.6. Personnel

It was recognized that viewing video footage of catch processing's as a full time job would likely lower the quality of the audits as this can become a tedious task. Therefore, student workers were hired as video auditors on part-time contracts of 15 h per week. The first month of employment would serve as a training period where a senior video auditor would look through videos with the newly hired video auditor. To verify the validity of audits, 10% of all audited video sequences would be re-audited by another video auditor to double-check the discards. If discrepancies occurred the video auditors would go through the specific video sequence together to investigate when and why the assessment differed. Four students served as auditors in 2015 and 2016.

3. Results

3.1. Malfunctions and countermeasures

Table 2 presents a list of reported errors during the years 2010–2016 and what was done to counter these. The total number of audited hauls was 7,690, meaning that for the whole period 2010–2016, 11.4% of video sequences selected for audit turned out to have an error, ranging from the video sequence being non-existent so that no audit could be done, to light reflections or smudge on the camera lenses being a nuisance for the video auditor.

3.2. Time used per audited haul

Technical developments served the purpose of enhancing the quality of the recorded data and reducing the time needed for auditing a haul. As the majority of participating vessels had conveyor belts and these tended to include the hauls with the largest volumes of discards, the developments mainly focused on optimization for vessels with conveyor belts. Method 4 lowered the average time needed for video audit of hauls from vessels with conveyer belt compared to the average

Table 1
Summary of audit methods applied in the CCQM. Species identification was based on human interpretation for all methods.

Audit method	Recording specifics	Audit grouping and coverage	Duration
Method 1	Spreadsheet recording. Human estimate of mass based on length and condition. Data recorded as kg for all audited groups.	All discards recorded. Grouped as Other or as Cod.	April 2010 – January 2015
Method 2	Custom interface and integrated database. 5 cm length interval record based on human interpretation with grid overlay as support. Record of number of each discard per length group. Automatic mass estimate based on mass-length equation.	Discards of cod, haddock, whiting and saithe recorded. All other discards ignored.	January 2015 – October 2015
Method 3	Same as Method 2.	Discards of cod, haddock, whiting, saithe and hake recorded. All other discards ignored.	October 2015 – July 2016
Method 4	Custom interface and integrated database. 0.1 cm length estimate recorded based on measuring line. Automatic length and number recorded based on human image analysis. Automatic mass estimate based on mass-length equation.	Discards of cod, haddock, whiting, saithe and hake recorded. All other discards ignored.	July 2016 – December 2016

Table 2
List of reported errors during the years 2010–2016 and what has been done to counter these.

Type	Number	Share	Countermeasure
Discard hard or impossible to identify	286	32.6%	Replacing cameras to get clearer view. Adding cameras to get continuous view of fish. Communicating with fishers on adaption of working routines (e.g. instruct fishers to stop tossing fish or ensure clear view of baskets with discard)
Dirty camera	168	19.1%	Applying NanoCover/Rain Repellent (Turtle Wax) to the lenses to reduce the risk of smudge sticking to the lenses. Increase fishers' awareness on cleaning procedures by introducing a video quality grade system
Blurry picture	154	17.5%	Higher resolution and video quality of cameras
Water droplet	119	13.6%	Tilting cameras whereby water droplets aggregate in the corner or bottom of the camera view rather than in the center
Video lost	59	6.7%	Transmit video data via the internet whereby manual replacement of hard drives ended. This removed the risk of damage or loss of hard drives which had previously accounted for virtually all lost videos
Fisher blocking camera view	33	3.8%	Reposition cameras to avoid areas where daily work routines would block the view
Video gap	28	3.2%	Using a more robust EM system
Camera breakdown	25	2.8%	Using a more robust EM system/cameras
Light reflection or lights are off	6	0.7%	Light reflection might be countered by repositioning cameras. Periods with the lights turned off was not an issue after 2014 as the new camera system included infrared video recording
Total errors	878	100.0%	

Table 3
Average and standard deviation for video audit times, haul duration and catch processing. Audit and haul times are presented for all years (2010–2016) as well as for the last six months of 2016 where Method 4 was employed. Data on catch processing duration is only available for Method 4. CB = Vessel with conveyer belt. NCB = Vessels without conveyer belt. *Catch processing times could not be made for gillnetters. These averages are therefore solely for trawlers or Danish seiners without conveyer belt.

Parameter	Vessel group	Average [min]	Standard Deviation [min]
Audit time, All years	CB	30.5	28.0
Audit time, All years	NCB	29.2	25.2
Haul time, All years	CB	322.9	108.4
Haul time, All years	NCB	236.8	155.8
Catch processing time, Method 4	CB	75.8	41.5
Catch processing time, Method 4	NCB	90.3*	91.9*
Audit time, Method 4	CB	21.4	15.3
Audit time, Method 4	NCB	35.0	42.7
Haul time, Method 4	CB	281.8	103.1
Haul time, Method 4	NCB	266.4	255.7

audit time for the full duration of the CCQM (Table 3). For Method 1 (Trial start to January 2015), the average time ratio (audit time/haul duration) was 0.151 (± 0.164) for vessels with conveyer belt and 0.158 (± 0.149) for vessels without conveyer belt, meaning that the audit time was roughly 15% of the haul duration on average for the first audit method. This fell with Method 2 (January 2015 to July 2016) to 0.047 (± 0.035) for vessels with conveyer belt and 0.094 (± 0.072) for vessels without conveyer belt. Changes in average times were negligible between Method 2 and Method 3 but Method 4 with more precise length estimates (July 2016 to trial end) led to a rise in the average time ratio to 0.093 (± 0.091) for vessels with conveyer belt and 0.122 (± 0.077) for vessels without conveyer belt (Fig. 2).

3.3. Digital data transmission

During 2015 and 2016 the transfer rate fluctuated between 5 megabit per second (Mbits/s) and 90 Mbits/s, with the majority of rates at 10–20 Mbits/s. Depending on the length of the fishing trip and the length and quality of video footage, the accumulation of data would differ. Whether a full data transmission was possible depended on the size of the data accumulated, transfer rate and port time. Participating Danish seiners and gillnetters had sufficient port time to transfer the recorded data on all occasions in 2015 and 2016. However, with an average data accumulation of 71.4 ± 15.5 GB per trip, demersal trawlers would on average need approximately 8 h of port time for a full data transmission given a 20 Mbit/s transfer rate. As transfer rates of 20 Mbit/s were not achieved at all times and due to port times as short as 4 h, the participating demersal trawlers accumulated data on the on-board data storage. When a vessel entered port the oldest data would be transmitted first. If a full data transmission could not be achieved, the recorded data from the next fishing trip would be added to the previous. This lead to a spiraling effect because more and more data had to be transmitted the next time the vessel was in port. This meant that the time lag between video recording and video audit was larger for some trawlers than for Danish seiners and gillnetters. On one occasion in 2015, it became necessary to manually exchange a hard drive on a demersal trawler in order to catch up with the accumulated data load. In all other instances, the storage capacity of 1 TB on hard drives and occasional longer port times made it possible to ensure full online data transmission. The increase in transfer rates in the last half of 2016 reduced the risk of data accumulation as the standard transfer rate of 50–90 Mbit/s more than halved the time needed for full data transmission.

3.4. Frequency distribution

Methods 2–4 made it possible to plot the number of discards pr. species pr. length interval in a frequency plot (Fig. 3). Of the five audited species, hake had the highest number of discarded individuals (1363 individuals on average per month, equal to 20,440 individuals recorded during 2015–2016), followed by saithe (1070 individuals on average per month), haddock (343 individuals per month), whiting (332 individuals per month) and cod (128 individuals per month). In terms of discards above the MCRS, hake in the North Sea had the highest percentage (99.35% of discards > MCRS) followed by saithe in Skagerrak (90.13%), whiting in Skagerrak (83.54%), hake in Skagerrak (78.32%), haddock in Skagerrak (78.21%), cod in Skagerrak (70.56%), whiting in the North Sea (69.24%), saithe in the North Sea (56.64%), cod in the North Sea (45.95%) and haddock in the North Sea (37.76%). A logistic regression model was used to test whether discard frequency below or above the MCRS depended on the management area (Skagerrak and North Sea). No statistically significant dependency of management area was found for any of the audited species. Non-compliance with the LO has been detected as haddock discards have been identified in both years despite haddock being subject to the LO in 2016 (EU, 2015).

3.5. Estimation of costs

In 2016, there were 396 Danish fishing vessels above 12 m in length

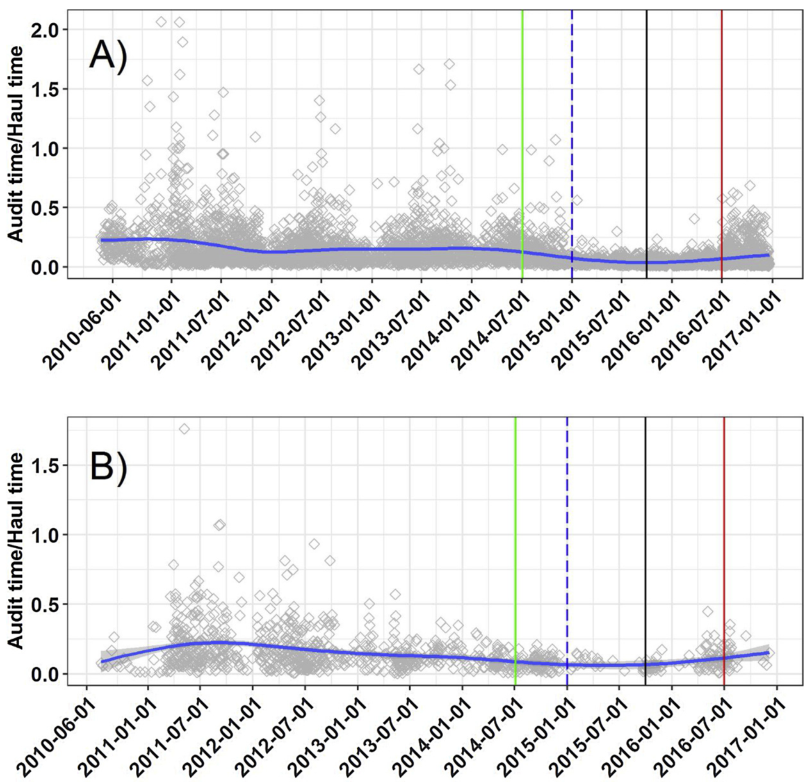

Fig. 2. Video audit duration/ haul duration divided by vessels with and without conveyor belt from 2010–2017. A): Vessels with conveyor belt. B): Vessels without conveyor belt. Green vertical line represents the first replacement of EM hardware and first use of the grid overlay and the database with interface software for audit, blue vertical dashed line represents the end of the audit of discard category “Other” and beginning of length interval audit for cod, saithe, haddock and whiting (Method 2), black line represents the inclusion of hake for length interval video audit, bringing the audited species to five (Method 3), red vertical line represents the onset of the final length measurement method using a line overlay for all recorded discards of the five audited species (Method 4) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

(STECF, 2017). Assuming that the 12 vessels in the CCQM are representative in terms of hauls and installation costs, a rough total estimation for an EM based control of all Danish vessels above 12 m in length can be calculated using the budget for the 2016 run of the CCQM (Table 4). For the estimate, the data gathered in 2015 and 2016 has been extrapolated to the rest of the Danish large scale fleet, amounting to roughly 1200 TB of data recorded each year. Based on these estimates, the total cost of having EM with video on all Danish fishing vessels above 12 m in length is roughly 1.7 million € annually recurring costs (2nd year total cost), with an additional 3.3 million € needed for initial investments in equipment, installation and training (1st year total cost of 4.9 million €). This corresponds to an average of 4200 € per vessel per year in recurring costs and 8300 € per vessel in initial costs. Besides the uncertainty in adjusting for all possible costs associated with an EM scheme it should also be noted that the estimate was adjusted to the fact that the audit coverage was above the minimum 10% requirement in 2016 (Bergsson et al., 2017). However there will be uncertainty as to whether this and other specifics for the 2016 run of the CCQM can be factored in directly. Likewise, data storage costs can vary significantly depending on the criteria for backup, data redundancy, data retrieval time and whether cloud options are permitted or only in-house storage is allowed.

4. Discussion

4.1. Main developments

Key improvements in the CCQM were; (i) transmission of EM data via the internet, which led to the possibility of adjusting the camera placements while watching the video footage in real time at the head office and reduced certain logistics involved in the project. (ii) the move from a spreadsheet recording system which relied heavily on human interpretation and manual entry, to a system with limited manual edits by video auditors and where the human interpretation was focused at species recognition and location of specific measuring points. The developments in the CCQM has allowed for better data on some aspects of the fisheries that are traditionally difficult to address. The recording of all discarded fish by length and estimated mass of several species makes it possible to analyze the discard size composition. Enhancement of audit precision and data acquisition came at the cost of increased audit duration relative to the haul duration. A clear understanding of the management aims motivating the introduction of an EM system is thus a key factor for designing the best trade-offs between costs and accuracy.

4.2. Reliability

Some of the lessons learned seem retrospectively as common sense (e.g. do not install cameras where their view will be blocked during catch processing’s working procedures). Nevertheless, when comparing the overall decline in the number of video sequences with malfunctions to the countermeasures done in the CCQM it seems evident that simple engineering solutions may be enough to improve the reliability of the EM system. We therefore included even the simple errors and countermeasures in this article to pass on the know-how gained from the trial. Ensuring clean cameras with unobstructed view of catch processing was a continuous issue during all the years of the CCQM. Drawing fishers’ attention to the issue often helped for a while but frequent follow-ups were needed. Several participants stated that they would forget that the cameras were present. Although this was a nuisance in terms of keeping camera lenses clean, the positive interpretation of such a statement is that fishers’ working procedures were not hindered or altered due to the presence of cameras. Participating fishers in the CCQM have previously stated that they forget the presence of the cameras (Plet-Hansen et al., 2017). Of the more technical developments employed to counter malfunctions, the possibility to transmit EM data via the internet was the greatest improvement. This measure countered an important cause of malfunctioning, i.e. lost or damaged hard drives during transport whereby relatively large quantities of video footage previously had been lost. The transmission also made it possible for video auditors to see the actual camera view while it was being installed, making it possible to make adjustments over the phone and

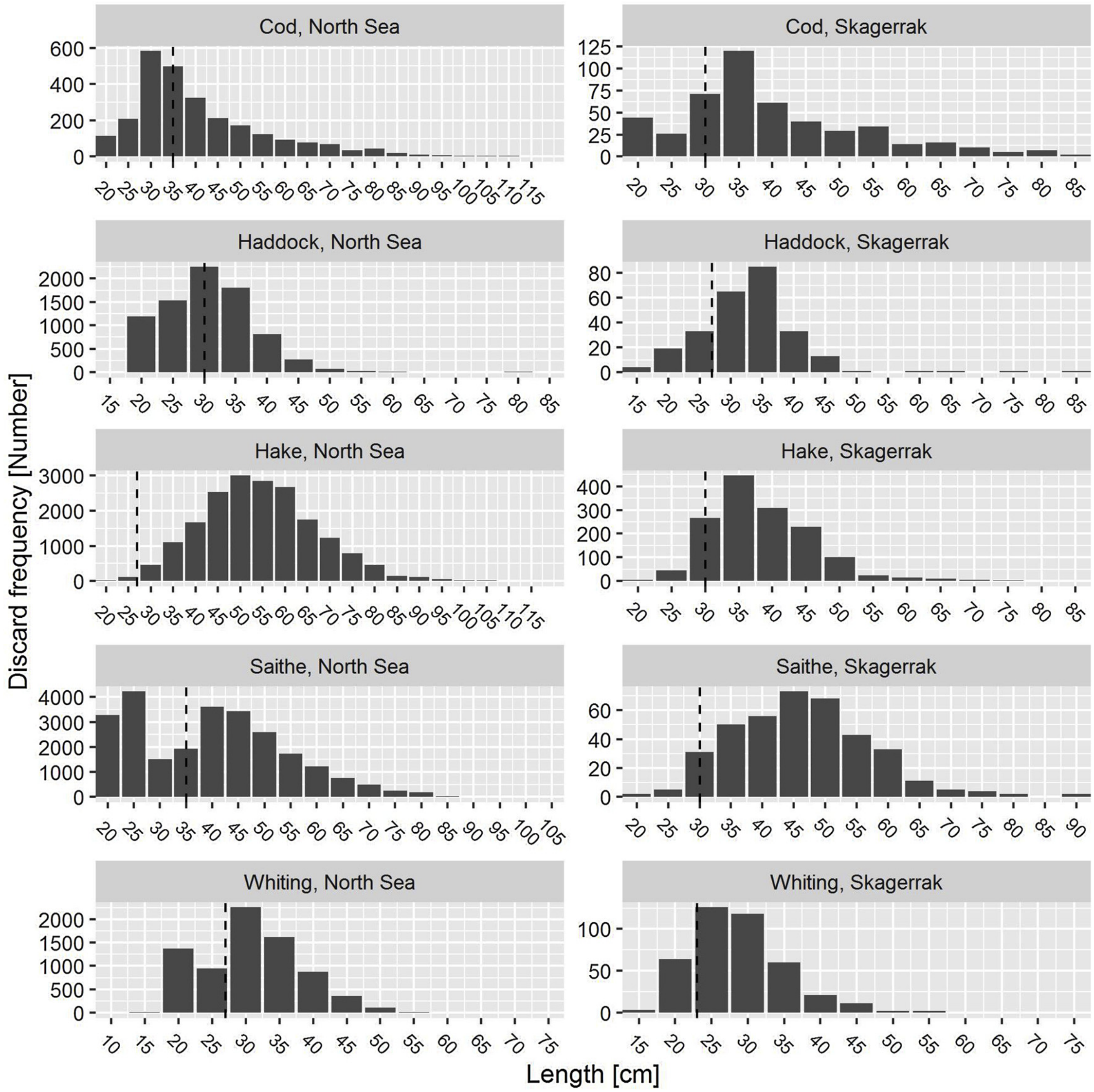

Fig. 3. Frequency distribution of discards in number 2015–2016 by length at a 5 cm interval. Dashed vertical lines mark the Minimum Conservation Reference Sizes (MCRS) for the species in the respective waters. Due to the different MCRS, discards are separated based on whether they occurred in the North Sea or Skagerrak. Note that hake was not audited until October 2015.

Table 4
Assumed expenses for EM monitoring. Values are based on the Danish Fisheries Agency's expenses during 2016, except for data storage expenses. *Average for several staff groups. **Data storage cost is based on a cloud storage solution for 1200 TB of data collected annually.

Expense type	Cost (€), one unit	Recurring	Cost (€), 396 vessels
EM equipment	4,139	Once	1,638,926
EM installation	4,027	Once	1,594,631
Video audit computer	1,074	Once	20,523
Training	902	Once	17,239
Salary, video audit	36,156	Annual	691,007
Salary, support and management*	48,190	Annual	515,410
EM software license	2,953	Annual	56,438
Additional software licenses	5,754	Annual	40,687
EM maintenance	1,119	Annual	158,198
Internet connection, rent and maintenance	392	Annual	155,034
Data storage**	46,025	Annual	46,025
Total cost, 1st year			4.9 million €
Total cost, 2nd year			1.7 million €

thereby optimize the placement of cameras. Finally, online transmission reduced the logistics involved in data transmission considerably. While data transmission via the internet could become challenged by large data quantities and short port durations, the increase in transmission rates and reliability as already experienced in 2016 should reduce this risk. The current trend of faster and more reliable internet connection only enhances the benefit of using digital data transmission.

4.3. *Cost of EM with video*

Depending on the setup for video auditors and the minimum audit coverage, the costs of video analysis can vary considerably. The estimate of the costs of fitting all Danish vessels above 12 m in length with EM should be seen as exactly this: an estimate. Due to inherent differences between vessels in terms of fishing operations, target species, vessel specifics, fishing areas and possibly crew mindset, it is a rough assumption to simply extrapolate the costs of the CCQM onto all Danish vessels above 12 m in length, including pelagic trawlers. Firstly, other vessels in the Danish fishing fleet will have different target species and areas, e.g. pelagic trawlers where the species composition is likely to be more homogenous than for demersal trawlers, whereby the audit time is likely to be shorter. Secondly, the vessels participating in the CCQM might have been those who would benefit from the trial setup or have adapted their fishing strategies to the trial, something that has been reported for a Dutch trial on EM and the CCQM has been criticized for (Msomphora and Aanesen, 2015; van Helmond et al., 2016). Thirdly, the minimum accepted audit coverage may be easy or hard to obtain depending on the needed viewer time for the vessel in question. This can vary due to multiple factors like catch composition and volume, working procedures and quality of video footage due to available setup for cameras on the vessel or how well the lenses are kept clean and whether the view is unobstructed. Fourth, the security and storage costs associated with the collected video material can vary a lot depending on how, where and for how long the video material is to be kept. One option is for vessels to store their own data for a specified period (e.g. 5 years) and making it mandatory for vessel owners to hand over video material to authorities upon request, following the principle of trucks' or airplanes' black boxes. Another option is for the fisheries authorities to collect and store all video material on their own servers and yet another option is to contract private companies for storage of video data. Depending on the approach, the associated cost can vary significantly. In addition, technical specifics such as redundancy, the split between archive data and immediate data and data storage retrieval time will also influence the cost of data storage. Lastly, the needed audit time and thereby associated costs will vary depending on the EM setup, vessels covered by EM, fishing areas and the number of species accounted for in the audit. The changes in audit procedures in the CCQM had a direct effect on the average audit time over haul duration where the swiftest audit method was the one with a 5 cm length interval record of species. The inclusion of hake is not possible to discern in the audit time but the change to a more precise length measurement increased the needed audit time. Another example is that Mortensen et al. (2017) reported an average of 41 min per haul used for video audit, whereas the CCQM had an average audit time of 21 min per haul for vessels with conveyor belt and 38 min for vessels without conveyor belt in the last year of the trial. The two trials had similar vessel composition and the EM system applied was the same but the trial conducted by Mortensen et al. (2017) also audited discards of plaice (*Pleuronectes platessa*) and *Nephrops* (*Nephrops norvegicus*) in addition to cod, saithe, hake, haddock and whiting. Additionally, Mortensen et al. (2017) covered vessels operating in the Baltic Sea and the audit procedures were different by not incorporating the gameboard setup used in the CCQM at the same time (2015). Besides the effect on needed audit time based on species coverage and analysis setup, the catch volume, catch composition and corresponding catch processing times have an effect on the needed audit time. Based on vessel and time of the year, fishing areas, target species, catch volumes and catch composition can change, meaning that the catch processing times for hauls and corresponding audit times can vary between vessels and on a temporal scale as well. The LO should make it easier and more uniform to audit catch processing because discarding shall not take place – at least not for species regulated by a quota or a MCRS. However, because discards will have to be documented if they occur and because exemptions from the LO exist, the LO may not actually reduce the needed audit time (EU, 2013; Needle et al., 2015). It is therefore difficult to estimate the final costs of applying EM as a large part of the fisheries management. The estimate does give an overall idea of the funding needed if EM with video should serve as a control measure and thereby gives a basis for comparison with other measures to ensure compliance with the LO.

4.4. Alternative compliance measures

A range of management tools other than EM for at-sea discard detection and estimation exist. These include aerial patrols, patrol vessels, drones, self-sampling and onboard observers. Norway is an example where a discard ban has been in place for decades and where extensive at-sea control by patrol vessels is used for enforcement (Gullestad et al., 2015). The Norwegian at-sea fisheries control is in the order of 2000 inspections per year and for this it is estimated that Norwegian Coast Guard spent approximately 70 million € in 2011 (Gullestad et al., 2015; James et al., 2019). Likewise, it is estimated that the cost of fitting all UK vessels above 10 m in length will amount to around 5.8 million € compared to the current cost of the UK fisheries control at roughly 23.3 million € (European Union Committee, 2019). In addition, aerial patrols, patrol vessels and drones are used for inspection, meaning that these capture only a snapshot of the fishing activities. Self-sampling allow for continuous coverage at a low cost, but the quality of the data may be questionable and therefore need verification (James et al., 2019). Onboard observers is currently the only MCS tool which can attain the same coverage level as EM and in fact for some metrics, such as age and mass estimates, allow for higher quality data than EM (Gilman et al., 2019; James et al., 2019). However, as other papers concerning EM with video have previously stated, the running costs of fisheries control with EM is lower than a similar coverage obtained with on-board observers and issues like observer safety at-sea and space limitations for an extra person on a vessel must also be taken into account (Gilman et al., 2019; James et al., 2019; Kindt-Larsen et al., 2011; Mangi et al., 2015; Mortensen et al., 2017; Needle et al., 2015).

4.5. EM with video as a management tool

The possibility to record all audited discards by length address a current challenge for the EU fisheries management as lack of data for this has been pointed to as a challenge for the promotion and management of the LO because different incentives are required based on whether catches are seen as unwanted because of size or quota constraints (Catchpole et al., 2017). The percentage of discards above MCRS is generally higher in Skagerrak than the North Sea but based on a test using a logistic regression model, this is not a significant effect. Except for cod and haddock in the North Sea, more than half of discards in numbers were above the MCRS for the audited species. Especially hake in the North Sea and saithe in Skagerrak deserve attention as more than 90% of the fish discarded were above the MCRS. The large majority of hake discards are above the MCRS. This could be driven by large shares of damaged fish or catch volumes exceeding the vessel quota as hake was not covered by the LO during the CCQM, meaning that over quota catches had to be discarded and hake has been identified as a species for which the EU quota allocations between Member States may be problematic due to shifts in species distribution (Baudron and Fernandes, 2015). However, as prices for hake are generally lower in Denmark than for instance for cod or haddock, it is possible that discards of hake may also be driven by a wish to keep storage capacity open for potential future catches of higher value species. As the CCQM was directed at monitoring cod catches, the inclusion of hake in the video audit was solely done for the purpose of gaining experience in species recognition. Therefore, analysis of potential discard drivers has not been performed in this study. Catchpole et al. (2018) identify damaged fish as the reason for the unwanted status in 92% of hake catches, "No market" accounting for additional 6%, leaving undersized fish as the reason for the remaining 2% of unwanted hake catches. The discards of whiting and saithe are roughly fifty-fifty above and below MCRS, whereas the majority of discards of haddock and cod are at or below the MCRS in the North Sea. This suggests, that for these two species, discarding could be driven mainly by size. However, it is important to note that cod was the species for which the CCQM was directed, meaning that participants had to acquire additional quota if they caught more cod than their initial quota. From a managers' point of view, EM with video is impossible to ignore for MCS purposes in fisheries managed with either Catch Quotas or discard bans. Verifying such management measures require on-board presence either full-time or at random. At-sea control can check for a certain level of compliance but to actually enforce a discard ban, on-board observers or EM with video seem currently the most trustworthy options (Hedley et al., 2015;

Plet-Hansen et al., 2017). Rather than opposing one against the other, using these two MCS tools in conjunction may be desirable to ensure the full validity of the fisheries management as both tools have advantages and disadvantages (Catchpole et al., 2017; Gilman et al., 2019). On-board observers allow for the greatest sample detail, but for compliance purposes, full coverage is needed. EM with video may lack sample details but allow for full coverage without the need of full review of video footage for compliance purposes. Video sequences selected for audit can be sampled randomly and used for verification of compliance with self-reporting regulations. In a European context, EM with video could thus verify whether requirements on discard entries in the eLog are complied with. Such verification of self-reporting allow for a lower audit coverage than if all discards are estimated through video audit. If non-compliance is detected, a larger percentage or even full audit of video footage from the given vessel can be conducted to support managers' claim of detected infringements. This actually happened in the CCQM in 2011 when underreporting of discards was detected for two vessels (Ulrich et al., 2015). In the last six months of the CCQM, recorded discards were stored as images in addition to the species mass and length estimates made by auditors. Such recording of discards will allow for precise documentation if fisheries managers need to take legal actions against vessels suspected of non-compliance. The fact that the video audit conducted in the CCQM detected non-compliance with the LO in 2016 emphasizes this. If the LO was fully complied with, no discards of haddock would have taken place in 2016 from the participating vessels as all of them had fisheries that were covered by the LO in the North Sea and Skagerrak and therefore had to bring all catches of haddock ashore. However, discarding of haddock was observed. This means that although fishers knew they were monitored by EM they still behaved in non-compliance with the LO. Whether this is because fishers forget they are monitored, lack knowledge about the species subject to the LO or something else is unknown. But it does highlight that EM is a tool for monitoring, and it must be supplied with enforcement actions (such as fines) to ensure that the LO will be complied with, if even fishers monitored by EM do not comply with the regulation, even though compliance with the LO was specified in the trial conditions. This is of importance not least when considering that critics of the results that can be derived from the CCQM have pointed to a selection bias in trials, because fishers with high compliance levels were more likely to participate in the trial (Msomphora and Aanesen, 2015). Despite its relevance, EM has so far only been used on a voluntary basis in the EU, although at the time of writing, the first uses of EM are being implemented as a response to the LO (STECF, 2018). A central reason for this is likely the reluctance towards EM which has been reported among fishers and relates to the perceived intrusion and surveillance level that EM represents (FiskerForum, 2018; Mangi et al., 2015; Plet-Hansen et al., 2017).

4.6. Future developments

The main future development for EM would be a larger uptake of this MCS tool in more fisheries, a trend that is indeed already ongoing as more and more fisheries around the globe either investigate or use EM as a MCS tool (van Helmond et al., in review). From a technical perspective, the next step forward for EM is likely the incorporation of automated image analysis. A scheme where computer software review recorded video sequences would allow for much faster audit than even the best trained personnel. Some of the reservations against video-based MCS measures could also be countered by such a scheme, because the surveillance would be non-human and therefore would only "see" the discards. Another option would be for automated image recognition to estimate the full catch prior to catch processing rather than estimating the discards. However, the current level of available image recognition software is to our knowledge still not sufficient to allow for species identification and automatic length measurements on the conveyor belt on-board commercial fishing vessels, although attempts have been made to achieve this (French et al., 2015) and developments within this field are rapid at the moment. The fact that automated species registration and length measurement in the actual trawl has now become available does support the possibility of having species recognition and length measurements run automatically in the future (Scantrol Deep Vision AS, 2017). If such automatization of video audit were to be incorporated, this would strengthen the quality of EM data regardless of whether the usage is for enforcement of compliance or estimation of discards. Unless all discards from all vessels are counted, the number of fish discarded will essentially still be unknown. Extrapolation of recorded discard data can be used and calibrated based on full account from EM-vessels but this will inherently carry the risk of inducing errors or bias. Automated image recognition may remove this issue by making it possible to identify virtually all discards in a fishery, leading to better data for stock assessments too. Some limitations in linking scientific survey data and EM data will remain. The identification of numbers, species and length is possible by use of EM systems as the one presented here, but the mass has to be calculated based on a length-mass relationship in order to compare the discards with quota settings. The use of the length-mass relationship will inherently ignore the variation in mass due to condition of each fish which can vary significantly (Schwalme and Chouinard, 1999). This will add uncertainty to the actual mass estimate derived from EM systems relying solely on visual discard audit. Adding dynamic scales to the EM system and incorporating discarding procedures for weighing discards would eliminate this uncertainty. However, this will likely extend the needed catch processing times due to the extra handling of unwanted catches which has been pointed to as an issue in other EM trials using either a compulsory system where discards would be binned in baskets or a system with individual arrangement of discards for clearer view (Ulrich et al., 2015; van Helmond et al., 2017). Additionally, this will not alter the fact that age determination is not possible with video footage, meaning that EM with video cannot address the difficulties related to comparing commercial mass-based catches with age-based scientific stock assessment. Linking EM with video to eLog records at a haul-by-haul basis allows for the determination of discards, discard rates and full catch account for each haul audited. From the spatial and temporal distribution of hauls, EM data can thus be used to highlight times and areas where discarding is likely to occur. Depending on the speed of video transmission and audit, such maps could potentially help fishers improve their spatial selectivity by consulting with continuously updated maps. Additionally, linkage of EM with video data to eLog data allows, at least in Denmark, for a linkage between EM with video data and grading machine data collected from sea-packing vessels (Plet-Hansen et al., 2018). This will allow for investigations of species' landings and discard size composition at the haul level, potentially shedding further light on the drivers behind the occurrence of unwanted catches.

5. Conclusion

The present study demonstrates that EM is capable of high precision detection of non-compliance with a discard ban and that developments in the transmission of EM data allowed for a smoother and more reliable MCS system. EM systems can still be improved, especially if automated image analysis could be incorporated. Our results point to possible reasons behind and patterns within the discarding practice and the scope and presence of some unwanted catches. Further analysis of discard patterns, both temporal and spatial, can be performed with the collected EM data presented in this study.

Contributors

- Clara Ulrich (CU) and Kristian Plet-Hansen (KP) designed the study.
- KP and Heiðrikur Bergsson (HB) did the data collection.
- Data analysis and interpretation were done by all authors (KP, HB,

CU).
- KP drafted the article.
- All authors made critical revision of the article (KP, HB, CU).
- Final approval of the version to be published was done by all authors (KP, HB, CU).

Declarations of interest

None.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.fishres.2019.03.009.

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Book chapter I - The Best Way to Reduce Discards Is by Not Catching Them!

Chapter 13
The Best Way to Reduce Discards Is by Not Catching Them!

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Abstract Under the Landing Obligation (LO) fishers will need to reduce or land fish that were previously discarded. In this chapter we look at how they might be able to do that by summarising a number of studies conducted in various European regions. We start by describing a series of "challenge" trials where fishers tried to reduce their discards by whatever (legal) means they thought best. In some cases, they were able to reduce unwanted catches, in others they were less successful. We also interviewed fishers not involved in the trials to ask them what they thought they could do. We explore their approaches which generally fell into three categories:

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more selective gear; tactical and strategic changes; and management changes. Scientific data (surveys, landings, and observers data) can also be valuable to help fishers to decide where and when to fish to best avoid unwanted catches and maximise opportunities to catch their quotas. We provide some examples of this type of approach, and also how these can be adapted for use as interactive online apps that fishers can use in planning or whilst at sea.

Keywords Challenge trials · Decision support tools · Discard avoidance · Fine scale mapping · Fish distribution · Fishers · Fishing strategies · Hot-spot maps

13.1 Introduction

Under the Landing Obligation (LO) fishers will need to reduce or land fish that were previously discarded. In this context, understanding how fisheries operate is central to understand how to manage them (Hilborn 2007; Eliasen et al. 2014). An obvious way by which fishers can reduce discards is via improved gear selectivity (O'Neill et al., this volume). Beyond that, the tactical choices made by fishers on "where, when and how to fish" can play a central role in reducing discards (Rijnsdorp et al. 2012; Dunn et al. 2011). This can be implemented in terms of top down control (e.g. closed areas). However, the need for management to provide bottom-up incentives to reduce discards is also well established (Rochet et al. 2014; Condie et al. 2014; Little et al. 2015; Pascoe et al. 2010).

In parallel, the ongoing improvements in data availability open for new and more precise knowledge. Analysis of discard observers' information (e.g. Anon 2011; Viana et al. 2011) provides a better understanding of spatio-temporal patterns of discarding. Catch locations and landings per unit of effort can be determined at fine spatial scales from Vessel Monitoring Systems (VMS) and logbook data (e.g. Gerritsen and Lordan 2011), and increasingly from Electronic Monitoring (EM) data (Plet-Hansen et al. 2017). Bottom trawl surveys can be used to map the locations of species (Fraser et al. 2008), spawning aggregations (Nash et al. 2012) and size structure (Shephard et al. 2011). This information can help fishers to decide where and when to fish to avoid having to catch unwanted fish.

In this chapter we look at how fishers themselves may be able to change the way they operate in order to reduce discards, based on a series of recent studies performed in several European fisheries in the frame of the EU research project DiscardLess (www.discardless.eu). We start by describing a series of 'challenge' trials where several individual fishers tried to reduce their discards by whatever (legal) means they thought best. We also interviewed other fishers not involved in the trials to ask them what they thought they could do. Their approaches generally fell into three categories: more selective gear; tactical and strategic changes; and management changes (Reid 2017). After a description of the trials and their results, we look at other tools to help fishers decide where and when to fish to best avoid unwanted catches, and maximise their opportunities to catch their quotas. At the time of writing this summary, a number of the individual studies presented here were still ongoing and/or unpublished, but a more detailed description of the methods used and preliminary results has been reported in Reid and Fauconnet (2018).

Management changes are beyond the scope of this chapter but are addressed in other chapters of this book.

13.2 What Can Fishers Themselves Do to Reduce Their Discards?

In a series of "challenge experiments", individual vessels and crew were challenged to reduce their discards by whatever legal means available. Intuitively, this could be by (for example) changing the fishing gear, or by changing their fishing tactics, perhaps by shifting areas or seasons. Each vessel fished first with their normal approach (control) and then with the modified approach (test) with the aim of minimising discards over a predetermined period (challenge trial). They reported the adjustments they made and why. Skippers were asked to set themselves a target for discard reduction between the test and the control trips, and this was the core of the "challenge". The targets could have been in terms of reducing discards of TAC species in general, or of those that represent the major 'choke' species in their fishery, i.e. the species for which the available quota is exhausted (long) before the quotas are exhausted of (some of) the other species that are caught together in a (mixed) fishery (Zimmermann et al. 2015). Scientists were sometimes placed on-board to collect catch data, and also to train crews in self-sampling. The catch data were then analysed by scientists to determine the degree of success at reaching these targets.

Challenge trials were done in three different countries and across a number of fisheries. The approach was slightly different in the three countries:

- Ireland – one demersal trawl vessel targeting whitefish (cod, haddock and whiting) and one targeting Norway lobster (*Nephrops norvegicus*) with additional catches of the same fish species (Calderwood et al. 2016).
- Denmark – 12 demersal trawl vessels mainly fishing cod and saithe, with three vessels targeting Norway lobster. The vessels towed a mix of single and twin trawl rigs, and were distributed between the North Sea, the Skagerrak, and the Baltic Sea. (Mortensen et al. 2017).
- France – three vessels targeting a mix of species including cod, whiting, squid, cuttlefish and some pelagic species. The vessels were all demersal trawlers, two < 18 m, and one > 18 m in length (Balazuc et al. 2016).

In Denmark, the main option explored by fishers was gear modification, and the data were mostly collected by the fishers themselves, supplemented with Fully Documented Fishery (FDF) methods (including Electronic Monitoring (EM) with cameras). In Ireland and France, the approaches included both gear and tactical modifications, with full observer coverage.

13.2.1 Gear Based Changes Used in the "Challenge Trials"

Changes to the fishing gear figured strongly in fisher's choices in all challenge trials. This was the main thrust of the Danish study, where the fishers used a variety of different gear modifications. These included:

- Changing mesh size in the codend of the net, usually to a larger mesh size, but in the Baltic Sea some vessels trialled reduced mesh sizes
- Inserting escape panels or separator panels into the net (with two codends for fish going above or below the panel)
- Topless trawl or modified mesh in an escape panel

In the French trials gear changes consisted of:

- The inclusion of a larger mesh cylinder in the extension (CMC)
- Separator panels with two codends
- Increased mesh size in the codend and extension, and T90 mesh

The only gear change in the Irish example was that one of the Irish vessels (the *Nephrops* targeting vessel) used a quad rig *Nephrops* net, with large mesh square mesh panels (SMP) in all four extensions.

The outcomes of these trials were somewhat mixed. In the Danish trials, nine vessels were able to reduce the discard ratio (Discards/Discards + Landings by species by weight) using the tested modifications (three in the North Sea, three in Skagerrak and three in the Baltic Sea), while two vessels (from the North Sea) actually increased their discard ratio and one North Sea vessel showed no difference. The improvements ranged from less than 2% for four of the vessels, 2–7% for four others, and, in one case, a 17.6% improvement (Fig. 13.1).

In the French trials, there was insufficient time after making the gear changes to collect sufficient data to analyse their performance. However, the vessel using the mesh cylinder (CMC) approach reported little loss of commercial catch volume, and in some cases reductions in discard volume. The separator panel with two codends could not be evaluated, but the skipper was still very positive and felt it had value. In general, the fishers did not feel that the changes in codend meshes achieved the results they had hoped for small fish, and there were concomitant losses in commercial sized fish (Balazuc et al. 2016).

In the Irish trials the use of the SMP in the quad rig allowed the vessel to keep fishing significantly longer before choking on the cod that was the main choke species during the control phase of the study. The results are shown in Fig. 13.2, and the reduction in over quota cod is clear, although there was an increase in over quota *Nephrops*.

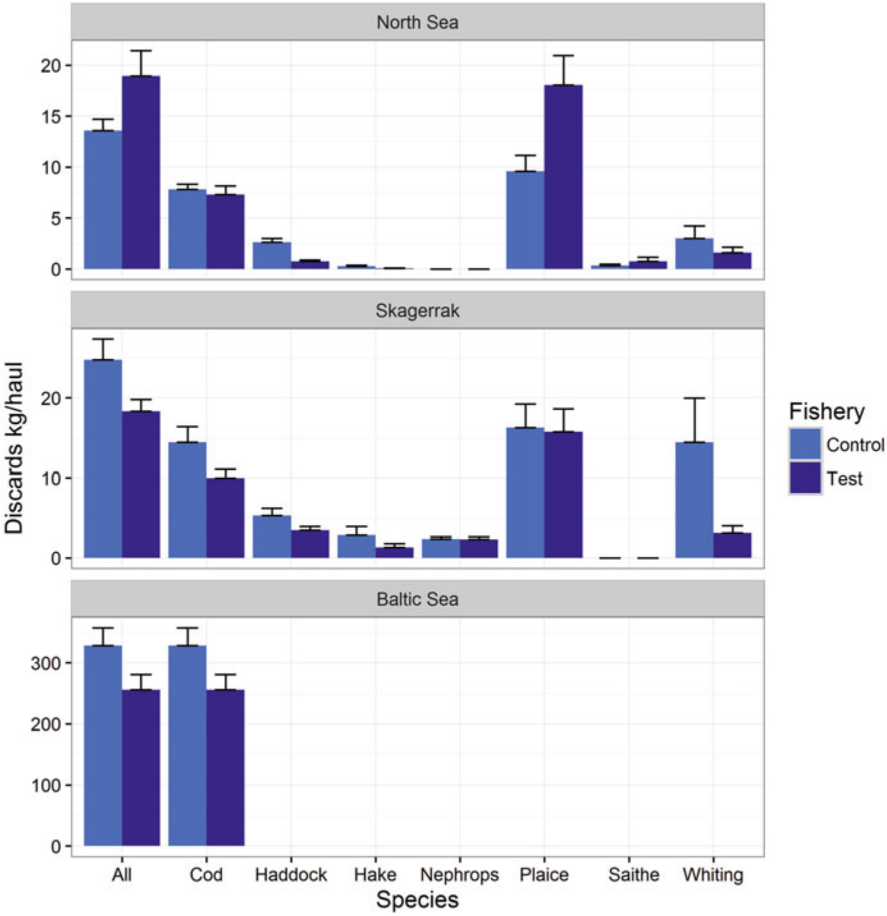

Fig. 13.1 Bar chart showing the average overall discards per haul from each area and the average discards per haul of individual species in each area. Error-bars signify standard error. Note that y-axes differ between areas. (From Mortensen et al. 2017)

13.2.2 Tactical and Strategic Changes Used in the Challenge Trials

Tactical and strategic changes to fishing to reduce discards were mainly tested in the Irish and French Challenge trials. In the Irish trials, the whitefish targeting vessel used changes in both the time of day and also in the depths of fishing. The vessel also tried to move between management areas to maximise the time fishing for the month. The main issue for this vessel in the control period was a very early choke on cod and haddock in all management areas. The combination of area and behavioural changes allowed a small change in choke time across all areas from 4 to 9 days. There was some evidence that the skipper was actually trying to avoid discards during the

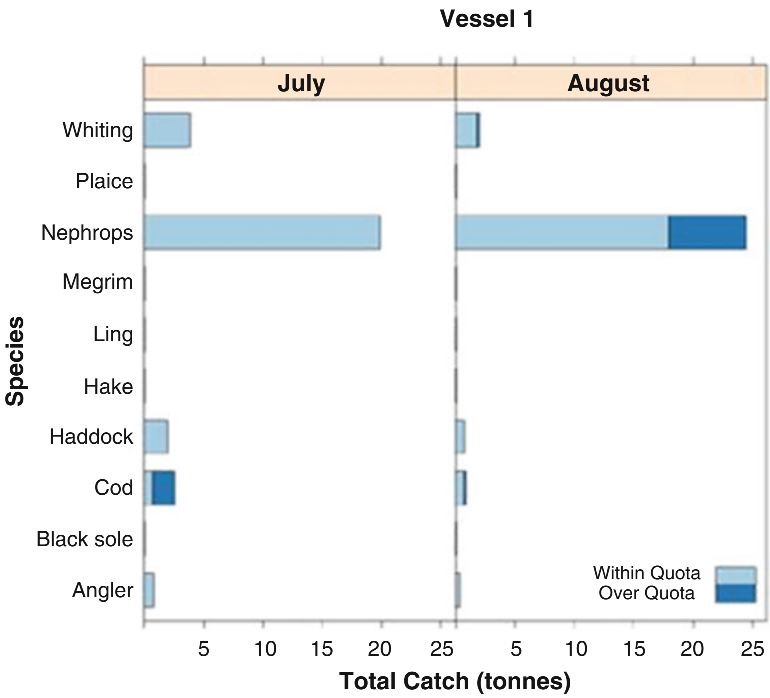

Fig. 13.2 Total catch of quota species for the Nephrops vessel during the 2 months of the trial, with a distinction between within quota landings (light blue) and over quota/< MCRS (over Minimum Conservation Reference Size) landings (dark blue). (From Calderwood et al. 2016)

control periods as well – he had somewhat higher discards in the months prior to the trials than in the control month during the trials. This may have impacted on the outcomes from the changes he made. The *Nephrops* vessel, while focused on the gear changes outlined above, also used movement between management areas to successfully reduce the choke problem (Fig. 13.3).

The strategic changes made by the French vessels were mainly focused on the potential for avoiding "sensitive" areas based on traditional ecological knowledge, characterised by high catch rates of quota species under MCRS. The outcomes suggested that the large vessel already did this in its normal practice, and that scope to do any more was limited. For the smaller vessels, their main operating area with high discards was within the three mile zone along the Channel coast, where almost 70% of their catch was usually discarded (Fig. 13.4). Avoiding this area would clearly help with their landing obligation (LO) requirement. The key issue was that, while discards are high in this zone, it is also their main area of operation. These are small, artisanal vessels, and this area is both close to their home ports and also sheltered from bad weather. As a consequence, the skippers were reluctant to avoid this area during the trials. However, it remains a potential valuable tool for discard mitigation under the LO, and ways to encourage the avoidance of this area should be explored.

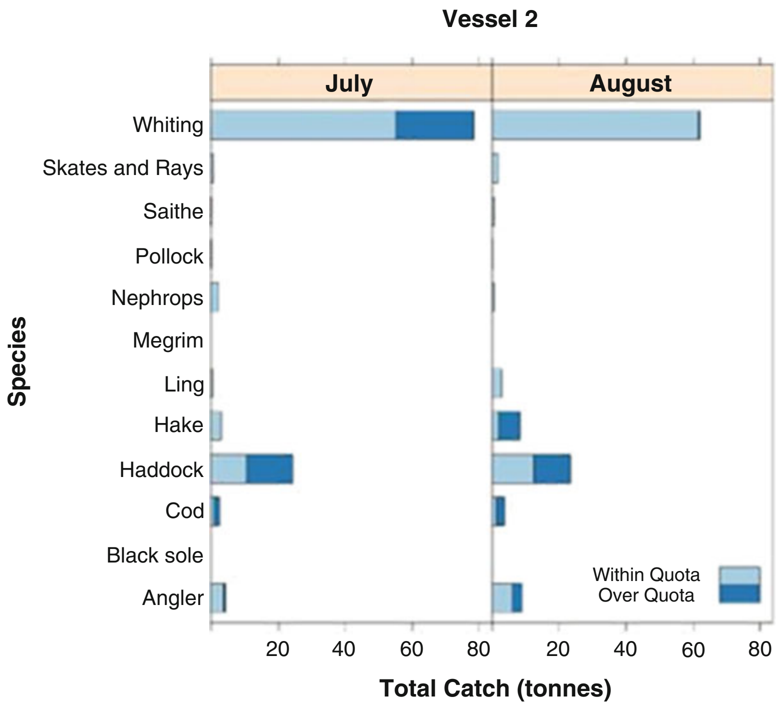

Fig. 13.3 Total catch of quota species for the white fish vessel during the 2 months of the trial, with a distinction between within quota landings (light blue) and over quota/below Minimum Conservation Reference Size (< MCRS) landings (dark blue). The vessel was able to reduce his over quota whiting catch, but could make little change in his over quota cod or haddock catches. (From Calderwood et al. 2016)

13.2.3 Conclusion

The use of modified gears to improve selectivity and reduce the scale of discarding showed some promise during the challenge trials. In all three cases, the use of added panels, changes in codend mesh size and configuration, modifications to the extension, and the use of separator panels with twin codends showed some improvements. However, it should be noted that these improvements were often quite small and would probably not solve all the problems fishers would face under a full implementation of the LO. Additionally, these were the fishers' own trials, and could not always be fully substantiated in a scientific context. One positive approach that could be taken, would be to enhance the institutional paths for a "fast-tracking" of such bottom-up initiatives (O'Neill et al., this volume).

The challenge trials showed that there was some scope for the use of both more selective gear and changes in behaviour, both locally, and in moving between management units, to reduce discards, and mitigate the impacts of the LO on fishing viability. Fishers in all the trials did believe that these changes could make some

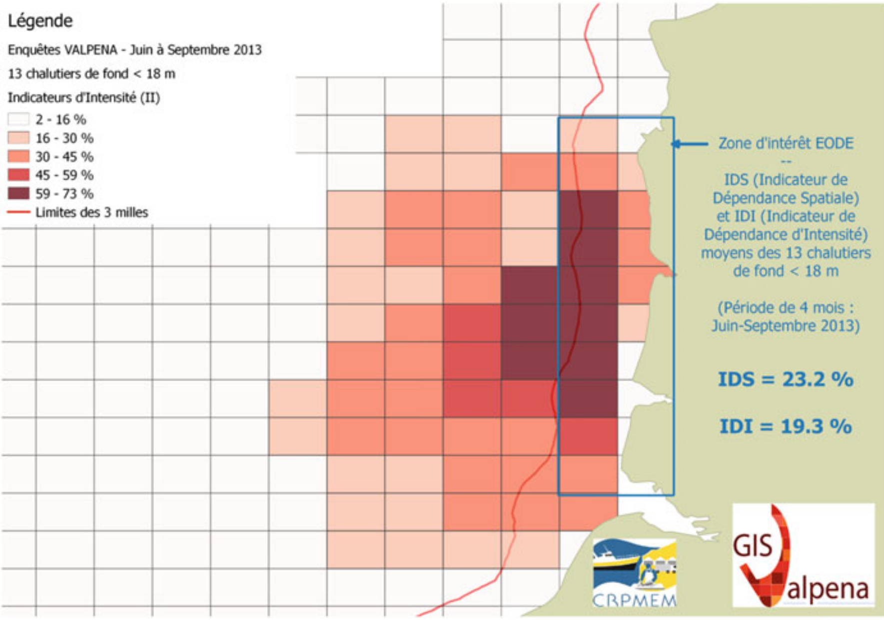

Fig. 13.4 Map showing Intensity Indices (II) of 13 trawlers under 18 meters over the period June–September 2013. (Source: CRPMEM NPdC-P and Gis Valpena)

difference, even if they did not work as well as expected in the limited context of the challenges. It should be noted though, that even when the trials were able to reduce discarding or the impact of choke species, the improvements were generally quite small. So, while such changes may help fishers comply with the LO by reducing discards, they are still not sufficient to avoid significant impacts on economic viability. Notwithstanding this, we consider it desirable to continue working with fishers on both gear and behavioural based responses to the challenges implicit in the LO. The trials were all successful in terms of the level of collaboration and in some of the outcomes, so such approaches should continue.

13.3 Where and When to Fish to Avoid Unwanted Catches – How the Scientists Can Help

Based on the challenge trials and interviews with fishers (Reid 2017), it was clear that tactical changes could help avoid unwanted catches, and we believe that more information would help fishers achieve this. We then looked for ways to provide the detailed knowledge that can come from using scientific data to illustrate the spatial and temporal distributions of the fish, catches and discards.

Fisheries institutions have access to a range of data. These include research vessel surveys showing abundance distributions, observer data showing detailed catch (landings plus discards) by commercial vessels, landings and vessel monitoring system (VMS) data showing where and when catches are made, and Fully Documented Fisheries pilot studies showing full details of complete fishing operations. We set out to use this information to develop the potential to assist fishers in making strategic choices to avoid discard. This included fine-scale, real-time mapping of catches and activity data, discards hotspots, juvenile surveys, etc. One aim was to provide Decision Support Tools (DST) to assess the role of "choke" species at the local scale. The role of the scientist here is as an advisor to fishers, about where and when they might fish to reduce choke problems and avoid unwanted catches.

No single approach was possible across all the examples shown below, and indeed was probably not desirable, as each had its own specific issues and context. These arose from a combination of how fish were distributed i.e. in discrete areas, or widely spread, and on the nature of LO requirements, e.g. avoidance of particular species or size classes, and the limitations in fishing imposed by geography and other legislation drivers.

DST can take many forms. At their simplest, these can be maps of where fish are found (from surveys), caught and discarded (from observers). However, more detailed analyses can be used to analyse spatial patterns and their variation, how discards and catches of numbers of species co-occur in space and time, or not. The information can also be represented in an interactive form using web-based apps. But the DST process can also simply be the provision of understanding discarding and its drivers, e.g. quota management rules, or about the interaction of economic profitability with discarding – is it economically better not to discard? We present examples of all these types of Decision Support information. These cover case studies from the North Sea, through North East Atlantic (European western waters) to the Mediterranean Sea. They cover many different metiers and fleets, from single to multi-species, using a wide variety of fishing gears.

13.3.1 Decision Support Tools Using Survey Data

Fisheries surveys are carried out across the EU and provide valuable data. The use of survey data in helping fishers to decide where and when to fish is illustrated with an example from the Balearic Islands (in the western Mediterranean Sea). The surveys were used to model the spatial patterns of species abundance for the main commercial species. The results from this were a series of maps of species distributions above and below MCRS, species overlaps, fishing grounds, discard hotspots etc. An example showing the density and persistence of thornback ray *Raja clavata* is presented in Fig. 13.5. In a second example, the degree of species overlap is presented in Fig. 13.6, illustrating where more than one species is likely to be caught together. Other data products from this study also made use of observer data to supplement the surveys.

In the Azores, habitat suitability models for 10 species of deep-water sharks and rays were developed based on survey data (Fauconnet et al. 2018). Deep-sea sharks,

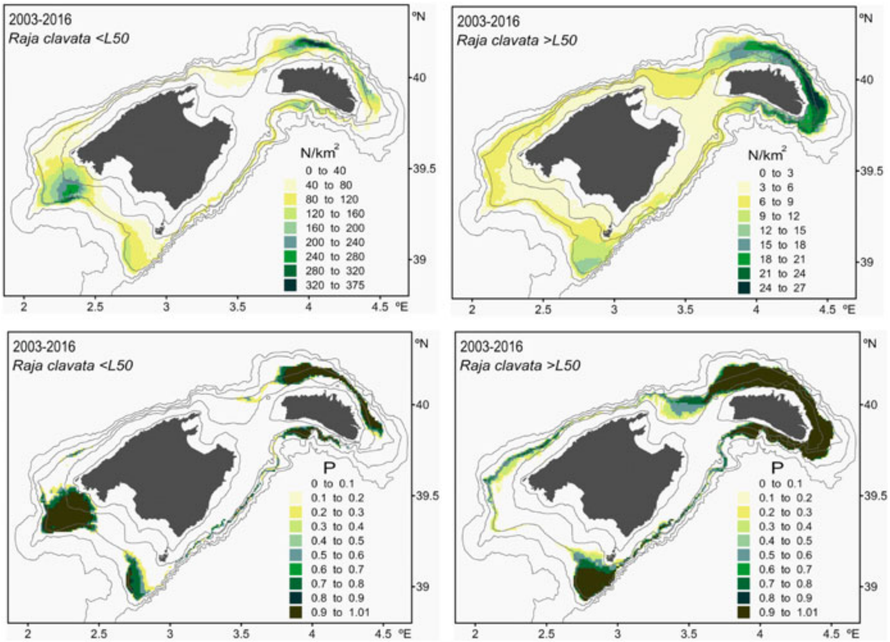

Fig. 13.5 Maps of density (N individuals/km^2; above) and persistence (P, fraction of years; below) of thornback ray individuals from the Balearic Islands under (< L50) and over (L > 50) the size at first maturity (73 cm)

even if only occasionally taken as bycatch of the deep-water longline fisheries in the Azores, could rapidly choke the fisheries of this Portuguese outermost region, as many of those species are currently managed under a zero TAC. Maps predicting occurence by species and combined occurence of all species at the range of the whole Azores EEZ were developed using data from demersal bottom longline surveys carried out from 1996 to 2017 (Fauconnet et al. unpublished data), to help fishers identify areas they should avoid to limit the risks of catching those species (Fig. 13.7). Composite maps combining the distribution of the main shark species caught by the bottom longliners, and by the deep-water drifting longliners were also created to better highlight the main areas to be avoided for those two groups of fishers. This information was completed using fine-scale information on deep-water shark spatial and vertical movements derived from acoustic telemetry data from 2 species: kitefin shark (*Dalatias licha*) (Fig. 13.8) and bluntnose sixgill shark (*Hexanchus griseus*). Telemetry data helped identify potential essential habitats for those species. The study highlights that areas to avoid fishing and limits in fishing depths at some time of the day could be promising mitigation measures for fishers to implement to avoid some species of deep-water elasmobranchs – but not for all.

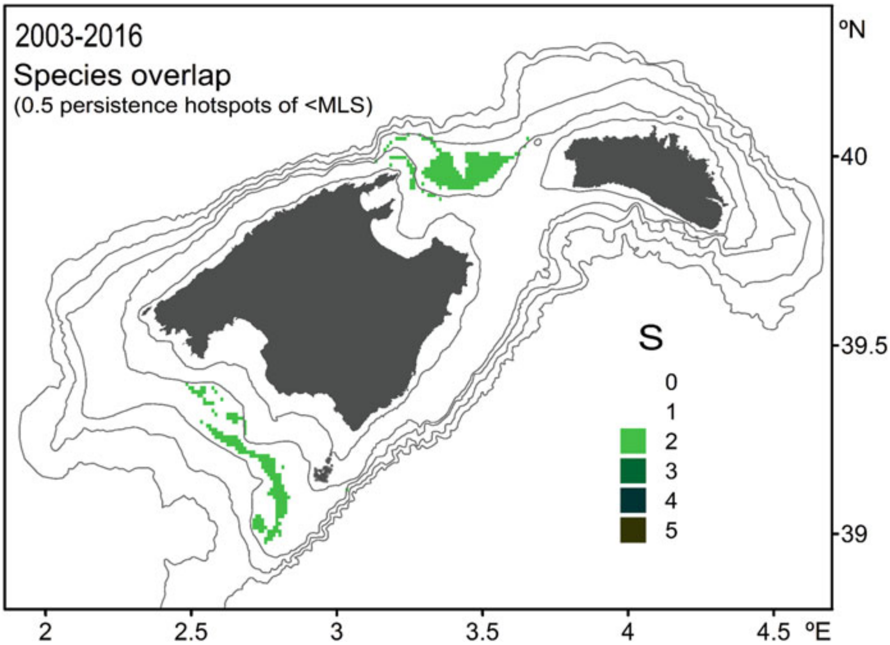

Fig. 13.6 Map of the number of species overlapping (S) in the mixed bottom trawl fishery from the Balearic Islands; S was obtained considering the Minimum Landing Size (MLS) of each species and a persistence level of 0.5

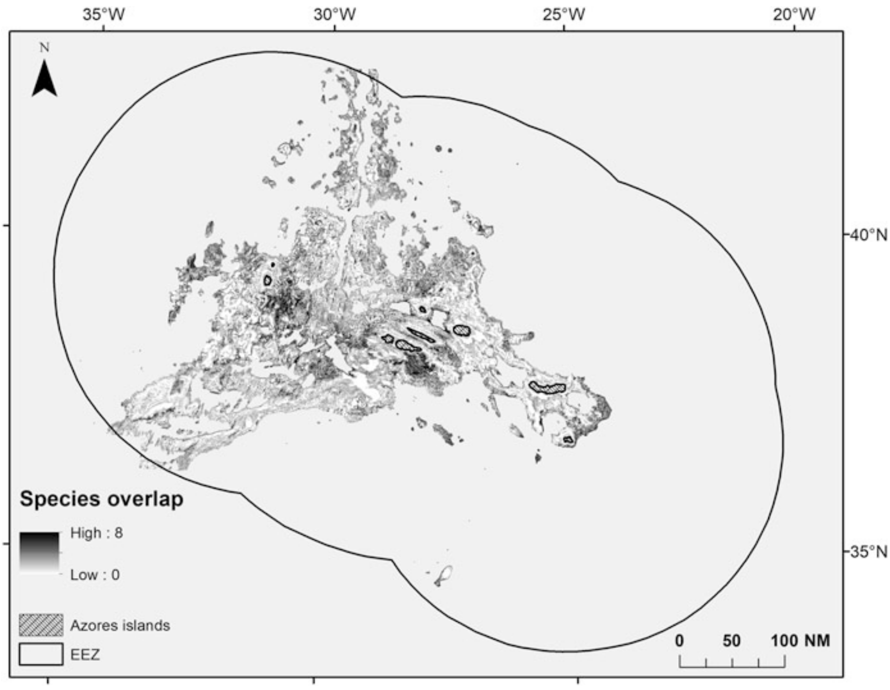

Fig. 13.7 Deep-water elasmobranchs hotspots distribution overlap based on presence/absence distribution of the 10 selected species. Uniform light grey represents areas with no data. (Fauconnet et al. 2018; Fontes et al. 2015)

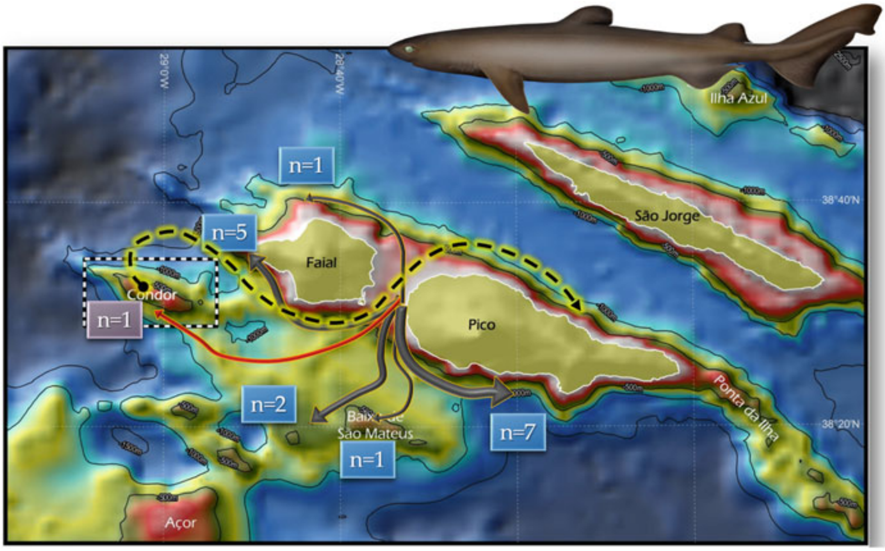

Fig. 13.8 Graphical representation of the movement ranges of individual kitefin sharks tagged with acoustic transmitters at the south of the Faial-Pico channel and monitored using deepwater acoustic receivers in the islands' slopes and neighbouring seamounts; boxes represent the number of sharks undertaking a particular movement. (Fauconnet et al. 2018)

13.3.2 Decision Support Tools Using Observer Data

Observer data come from on-board observers on commercial fishing vessels, and, like surveys, similar coverage is carried out across the EU. Their primary task is to record discards, but they also record fish that go to landings. Thus they represent very detailed information on catches, landed and discarded. It is only possible to deploy observers on a small proportion of all fishing trips, but we were able to combine observer data from France, Ireland and the UK for the Celtic Sea to provide a larger dataset to work on, and some of the results are shown here. Two different approaches are presented as examples of what information can be produced.

13.3.2.1 Where Are Discards Clustered Together?

This study is the first multispecies, fine scale, spatial analysis of landings and discards in mixed fisheries across a multinational context. The core aim was to use observer data to identify where commercial fish were landed and discarded and with what other species. Multivariate analysis (Principal Component Analysis PCA and hierarchical clustering) on combined observer data from Ireland and France between 2010 and 2014 grouped cells of space characterized by homogeneous species profiles in terms of discards (or landings). Each cluster was then plotted on a map with a

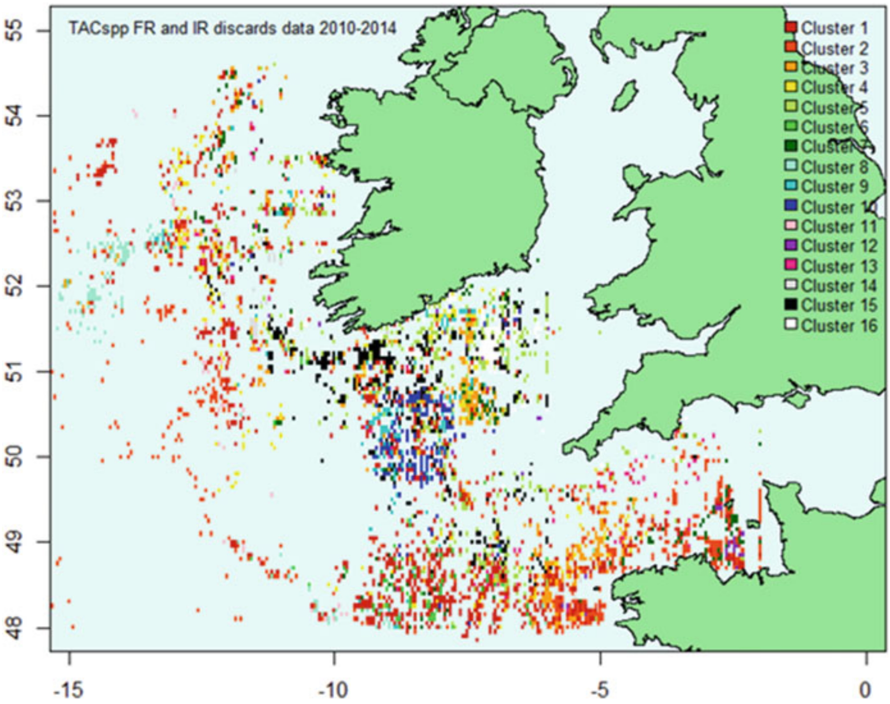

Fig. 13.9 Cluster maps of French and Irish discards. The same colour code was assigned to each 3′*3′ square belonging to the same cluster. This analysis was for TAC species only

colour code. It provides a global overview of discards and landings locations by species in the central region of the Celtic Sea. What was found was a highly structured fishing ground, with some of the clusters only found in a smaller part of the whole Celtic Sea. For instance, in the map shown in Fig. 13.9, there is a notable patch of the dark blue cluster 10 in the middle of the area. This cluster mainly represents observed discards of Norway lobster and spurdog (*Squalus acanthias*). But the more widely spread red cluster 13, was mainly composed of mackerel (*Scomber scombrus*) and sprat (*Sprattus sprattus*). While some discard clusters corresponded well to landings clusters spatially, this was less common than cases where no obvious common pattern was found. This result suggests that in the central Celtic Sea, landings profiles in terms of species may not predict discards species composition.

13.3.2.2 Mapping Catch Hot Spots to Avoid Unwanted Catches

A valuable support tool for fishers would be to have access to maps showing species abundance hotspots – that is, areas where there would be a high probability of catching a given species, above or below MCRS. This was carried out using a

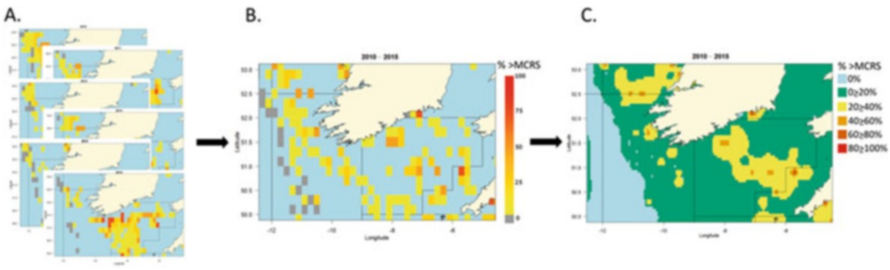

Fig. 13.10 Diagram showing the steps in the map production process. (A. Individual binned maps created for each year; B. Amalgamated map for all years identifying grid cells within consistent binned categories over multiple years; C. Final interpolated map (using inverse distance weighted interpolation)

detailed analysis of observer data from Ireland, France and the UK used as an indicator of the catches taken in the Celtic Sea. The analysis focused on mapping hot spots of CPUE and catch proportion for three key species; cod, haddock and whiting, and over and under MCRS. The analysis can be extended to any species, both commercial and non-commercial. The maps were based on consistent observations of particular catch rates, so only those locations where one would consistently (over 5 years) see high or low levels for these categories were used. The data were then interpolated to provide regional coverage (Fig. 13.10). The maps were then drawn together into a web-based app (discussed below).

13.3.2.3 Detailed Haul-by-Haul Mapping Using Electronic Monitoring Data

Another option to monitor catches is the use of Electronic Monitoring (EM) systems with video on board vessels that can monitor the haul-by-haul catch remotely. Such a system has been trialled in Denmark since 2008 (Bergsson et al. 2017; Ulrich et al. 2015). The analysed footage provides detailed information on discards, covering more trips and hauls compared to observer trips, for vessels carrying the system. An example is shown in Fig. 13.11.

Fine-scale information on landings and discards by haul can be combined with the landing price for the trip to map trade-offs between high-value and high-discard fishing spots, which can potentially complement the fisher's implicit knowledge on the best fishing locations (Plet-Hansen and Ulrich 2018). An example for a single vessel for which such a detailed information is available is presented in Fig. 13.12.

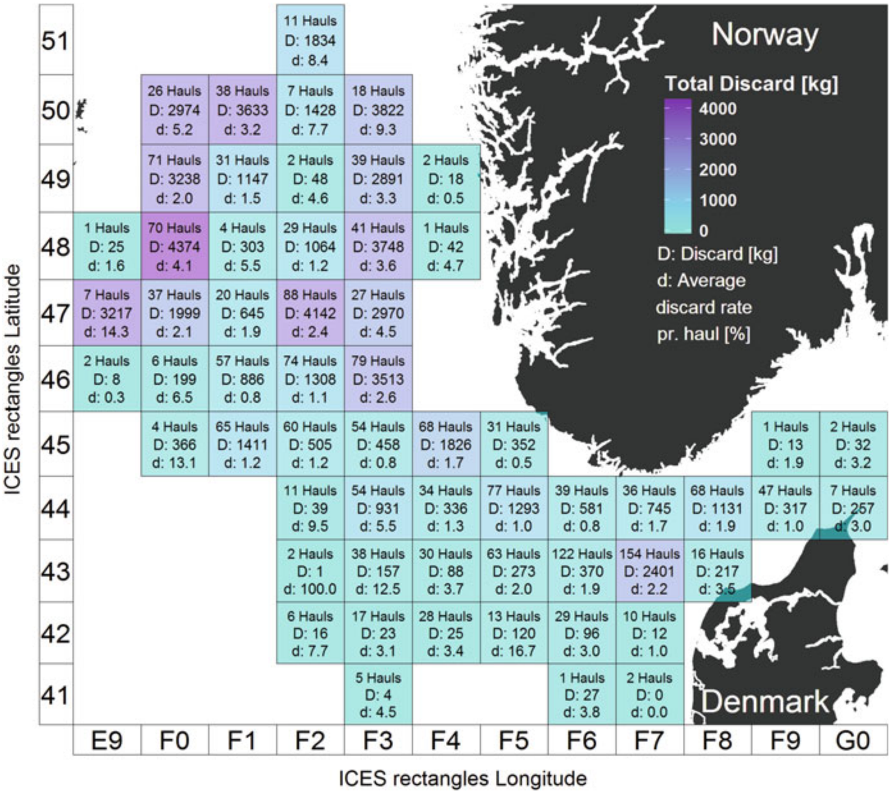

Fig. 13.11 Map of 2016 EM discard data for cod, hake, saithe, whiting and haddock from 12 Danish vessels (sampled hauls with video footage reviewed representing 29% of all their hauls that year). Cyan areas have low total discards in kg, purple areas have higher total discards. Each grid cell is an ICES rectangle. The x-axis shows the ICES rectangles' longitudinal ID, the y-axis shows the ICES rectangles' latitudinal ID. The number of sampled hauls conducted in each ICES rectangle by the 12 vessels is written together with the discard in kg (D), and the average discard rate (Discards/Catch) for the 5 species per haul (in %). (From Bergsson et al. 2017)

13.3.2.4 Combining Surveys and Commercial Catch Data to Provide Year-Round Abundance Distributions

Data from scientific surveys are not available for all times of the year but provide consistent yearly and spatially resolved abundance indices. On-board commercial data cover the whole year, but generally provide a biased perception of stock abundance. The combination of scientific and commercial catches per unit of effort (CPUEs), standardized using statistical methods (in this example a delta-generalized linear model), allows the description of the spatial and temporal (monthly) dynamics of fish distributions in the Eastern English Channel (Bourdaud et al. 2017). Using the scientific survey as a baseline, the degree of reliability of commercial CPUEs was assessed with survey-based distributions using the local overlap between

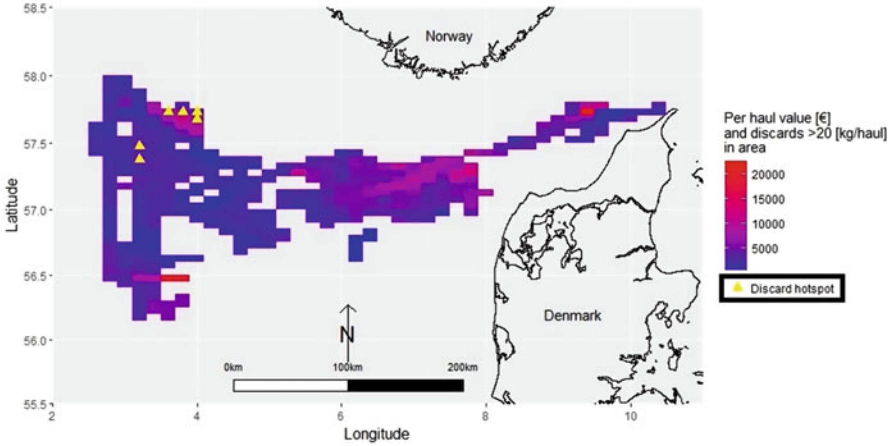

Fig. 13.12 Gridded map of the landing value per haul for a single Danish trawler. The red colour represents the greatest value per haul. The yellow triangles represent the areas of high discard volumes. The discard hotspot areas often coincide with high value hauls but importantly, there are also other high value areas without such high discard levels. (From Plet-Hansen and Ulrich 2018)

distributions. The broader spatio-temporal estimated distribution of the species agreed with qualitative information from the literature, especially for cuttlefish, and this is illustrated in Fig. 13.13. Fine scale consistency (using cells of 0.3°*0.3°) between survey and commercial data was significant for half of the 19 tested species (e.g. whiting, cod). For the other species (e.g. plaice, thornback ray), the results were inconclusive. The approach allowed a more representative mapping of the abundance distribution across the year, that can then be used in both targeting, and avoidance in the context of the LO.

13.4 Web-Based Apps to Help Fishers Plan Where and When to Fish to Avoid Unwanted Catches

In many of the analyses in this chapter, the scientists concerned have been able to produce information, usually in map form, that has the potential to help fishers target their activity to avoid unwanted catches. To make this practically useful, and useable, scientists have started developing a range of web-based apps both to present the information, but critically, to allow the fishers to work with it in their own way. In three of the examples given in the above descriptions, such apps have been developed and are, or will be, refined with fishers to make them as useful as possible.

One example developed in the Balearic Islands is presented in Fig. 13.14. The app allows fishers to choose the species and fishing ground of interest. They can then see

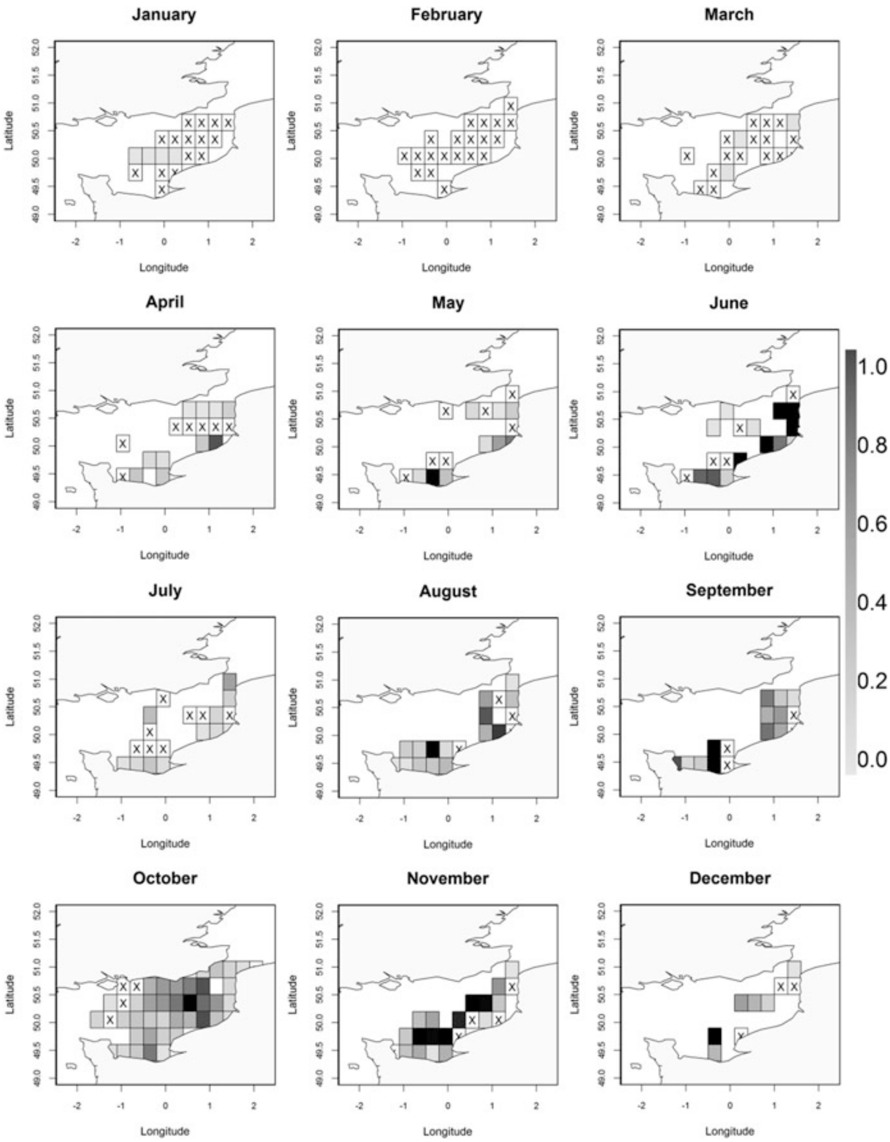

Fig. 13.13 Monthly spatial abundance distribution estimated from on-board commercial observations (OBSMER program in France) and scientific surveys (CGFS, Channel Ground Fish Survey) for cuttlefish. The crosses in the white squares (X) represent areas where no cuttlefish was ever fished during a month. (Figure from Bourdaud et al. 2017)

observer or survey data, as well as discard information, length and maturity data, and other information on the species and the fisheries.

A second example, developed for the Celtic Sea fisheries, is presented in Fig. 13.15, where the fishers can choose the species (or size class) of interest, and

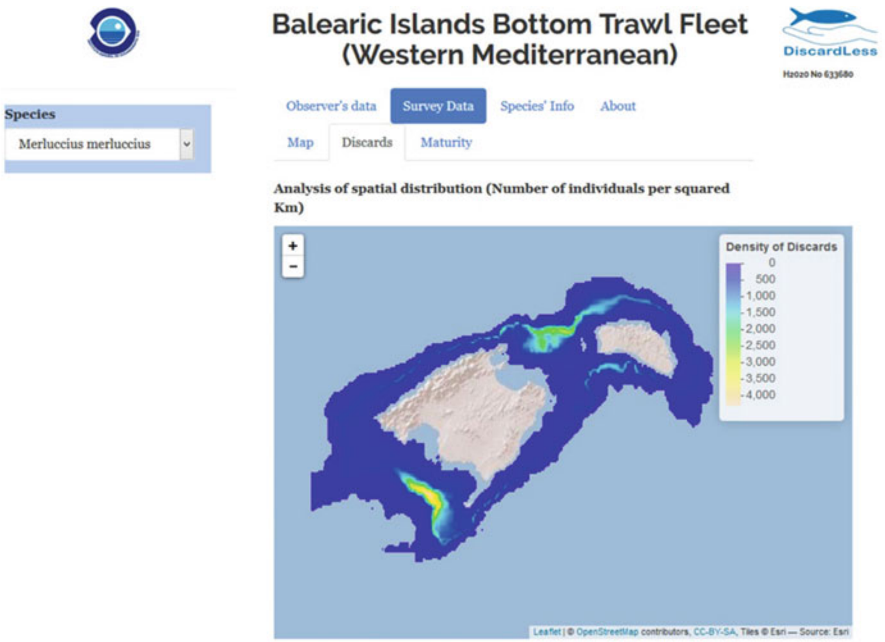

Fig. 13.14 Snapshot of the Shiny App produced as a decision support tool to assist fishers in the Balearic Islands to make choices of fishing location to avoid discards. Density map (number of individuals per km2) of hake discards (individuals under the MLS = 20 cm) is shown

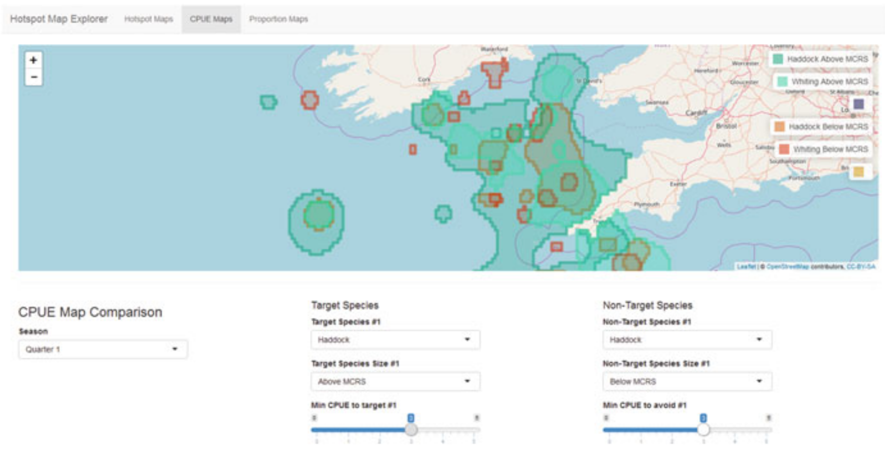

Fig. 13.15 A screenshot of the Shiny App developed to allow stakeholders to select the size, species and quantity of fish they would like to target and/or avoid during different seasons. The resultant map displays layers allowing fishers to balance trade-offs of target and non-target to optimise catch composition.

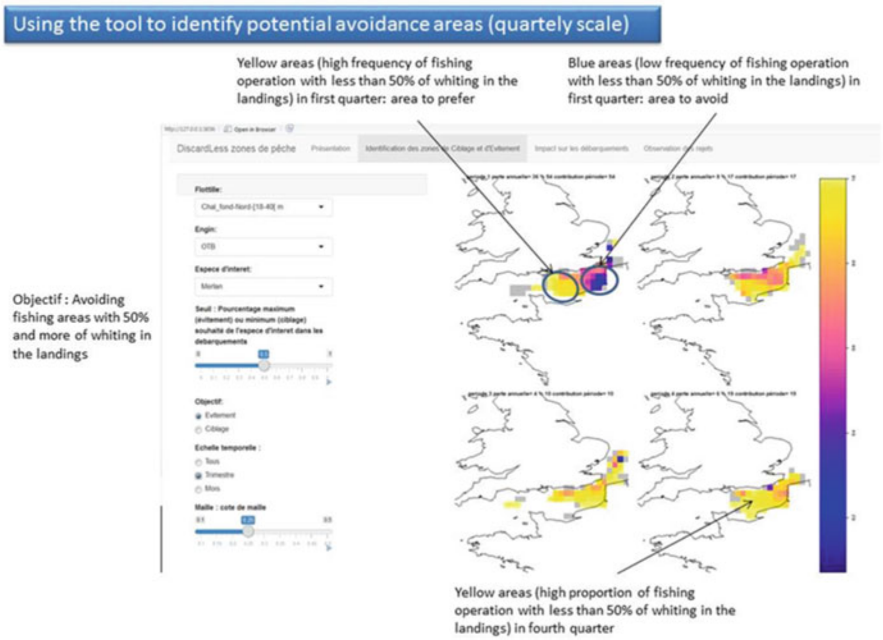

Fig. 13.16 An example of the web-based app for the English Channel showing a variety of ways to present information to avoid discards

then map CPUE or catch proportion at the selected level of intensity. They can also map a number of species or sizes together on one map, and change the levels, to help choose the best places to avoid or to find particular species or sizes. The app represents a DST for fishers, and is still under development, but it is planned to incorporate additional species as well as discarding hotspots. The app is a prototype and will be developed working with individual fishers to best fit it to their needs.

The final example is for the fishery in the Eastern English Channel discussed earlier. Again, the app offers the fisher a variety of choices for presentation (Fig. 13.16). They can choose the species, gear and fleet, and look at landings, discards or survey data. As in the Celtic Sea example, fishers can define a maximum or minimum proportion of a given species in the landings that he is willing to accept depending on the objective i.e. avoiding or targeting the species. The time scale over which the maps are presented can also be controlled, either for a year, quarter or month.

13.5 Conclusions

The original idea we stated in the title was “The best way to reduce discards is by not catching them!” The work presented in this chapter shows some of the ways that this could be achieved.

Gear based changes in selectivity remain the most common, default, way to do this, and we present here some of the broad range of such approaches available. Many of these have been developed by gear technologists, but many also by working fishers or netmakers. In many of our studies, we found that fishers remain innovative and willing to explore the use of different gears to reduce unwanted catches.

Behavioural changes by fishers, i.e. tactical changes in where and when to fish, are a second route to avoiding unwanted catches that have attracted less attention than gear-based approaches. In the challenge trials described here, fishers attempted both gear and behavioural changes in their fishing practices. In some cases, these changes reduced unwanted catches but not in all. One of the reasons for this advanced by several fishers involved in the work was that they lacked the information needed to help them choose where and when to fish to minimise the unwanted component.

It is beyond doubt that fishers know their own fishing activity far better than any scientists could. They are, after all, observing it on a daily basis over many years. But, equally, scientists have information that fills in the wider picture on distributions and abundances of fish, both wanted and unwanted. Taken together, fishers' and scientists' "knowhow" can give the working fisher the best chance to reduce, or possibly eliminate, unwanted catches. We have shown here how surveys, observers' information, landings data, etc. can provide useful information on where the fishers are likely to encounter a given species or size class of that species, as well as those fish commonly encountered together. It needs to be emphasised that this information should be seen as providing a probability of encounter or not, rather than a certainty. The take-home message from this is that there is more chance of approaching the objectives of the landing obligation by combining fishers' and scientists' knowledge than by working apart.

Another key message is that we can identify several different approaches that could help reduce discarding, but they all tend to be specific to local conditions. It should be possible to export the approaches to other fisheries, but only in broad terms. Essentially, the causes of discarding are common, but the solutions tend to be local and specific.

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Supplementary material

S1. Basic spatial data considerations and species distribution model overview

S1.1 Vector-based spatial data

Vector-based spatial data represent the real world as points, lines and polygons. As a whole, vector data have the advantage of high accuracy (if data is at a level that support this), the graphical output tends to be aesthetically pleasing and proximity and network analysis work well for vector data. Vector-based data is best suited for network analyses (Burrough and McDonnell, 1998). Classic network analysis examples are calculation of shortest path, where the aim of the analysis is to find the shortest path in time or distance (Heywood *et al*., 2011). However, vector data require a lot of processing for spatial analysis and continuous data tend to be problematic to display as vectors (Balstrøm *et al*., 2006; Bivand *et al*., 2008a; Burrough and McDonnell, 1998).

S1.2 Raster-based spatial data

Raster-based spatial data operate by assigning and storing all entities in cells, whereby the real world is represented in grids, just as pixels. The basis for raster began in the 1970ies with the first satellite imagery (Balstrøm *et al*., 2006; Burrough and McDonnell, 1998). In order for computers to store and analyse the images, geographical representation had to be in a format that could be read and interpreted by computers. Raster-based spatial data perform better then vector-based spatial data for continuous data and quantitative analysis as well as mathematical modelling (Balstrøm *et al*., 2006; Heywood *et al*., 2011). However, fine scale raster grid size can result in very extensive data volumes, while cruder grid size can lead to loss of information (Balstrøm *et al*., 2006; Bivand *et al*., 2008a; Burrough and McDonnell, 1998).

In practice, both vector- and raster-based spatial data function well in computer software because of technological developments, although certain operations do perform better for one or the other (Table S1). Raster-based data is best suited for overlay or area analyses, where one or more raster layers are created. A classic example is heat maps where a value gradient is visualized by a colour gradient to highlight favourable or unfavourable areas, for instance of flooding risk or discarding hotspots (Burrough and McDonnell, 1998; Heywood *et al*., 2011).

Table S1. Main advantages and disadvantages for raster and vector-based spatial data

Raster		***Vector***	
Advantage	**Disadvantage**	**Advantage**	**Disadvantage**
(a) Pixelated format which is easy to produce (b) Perform quantitative analysis well for discrete and continuous features	(a) Linear features and network analysis are not possible (b) Generalized representation of features (c) Fine-scale mapping create vast data tables	(a) Geographic accuracy and pleasing aesthetics because of linear features (b) Network analysis and proximity operations need vector data structures	(a) Perform poorly for continuous data (b) Complex processing and/or manual editing often necessary (c) Not possible to perform spatial analysis inside created polygons

S2. Species distribution models

Species distribution models (SDMs) is a wide group of statistical models used to combine ecological modelling with species observations to estimate the distribution of the given species (Elith and Leathwick 2009; Guisan and Thuiller 2005). Several approaches exist within SDMs, including:

- Classification Tree Analysis (CTA) (Valavanis *et al*. 2008)
- Random forest (RF) (Howard *et al*. 2014)
- Multivariate Adaptive Regression Splines (MARS) (BCCVL 2019; Valavanis *et al*. 2008)
- Flexible Discriminant Analysis (FDA) (BCCVL 2019; Hastie *et al*. 1994)
- Generalized Additive Models (GAMs) (Ciannelli *et al*. 2008; Elith and Leathwick 2009)
- Generalized Linear Models (GLMs) (Ciannelli *et al*. 2008; Kristensen *et al*. 2014)
- Generalized Boosting Models (GBMs) (Friedman *et al*. 2000; Torres *et al*. 2015)
- Surface Range Envelope (SRE) (Araujo and Peterson 2012; Stockwell and Peters 1999)
- Maximum Entropy (MaxEnt) (Merow *et al*. 2013; Phillips *et al*. 2006)
- Artificial Neural Network (ANN) (Dreiseitl and Ohno-machado 2003; Valavanis *et al*. 2008)

While this is not an exhaustive list, the presented model approaches cover a large share of well-established methods for SDM (Table S2).
As previously discussed, fishery dependent data is by nature sampled with a methodological bias. Inclusion of data from SIF or EM therefore need to be tailored with methods that can account for such methodological bias (Conn *et al*. 2017; Pennino *et al*. 2019).

*Table S2. Model overview and summary. Adapted from BCCVL, 2019 and Collins and McIntyre, 2015 and Openness Method Factsheet for Species Distribution Models, http://www.openness-project.eu/. (BCCVL 2019; Collins and McIntyre 2015)***.**

Model concept	Technique	Model examples	Variable types
Decision tree	Classification and regression	Classification Tree Analysis	Continuous and categorical
		Random Forest	Continuous and categorical
Regression	Linear model	Multivariate Adaptive Regression Splines (MARS)	Continuous and categorical
	Classification and Multivariate Adaptive Regression Splines (MARS)	Flexible Discriminant Analysis	Continuous and categorical
	Additive model	Generalized Additive Models	Continuous and categorical
	Linear models, least square fitting and additive models	Generalized Linear Models	Continuous and categorical
Regression and decision tree	Regression decision trees and boosting method (combining several simpler models to improve model performance)	Generalized Boosting Model	Continuous and categorical
Environmental envelope	GARP-simulation	Surface Range Envelope	Continuous
Machine Learning	Maximum entropy	Maximum entropy	Continuous and categorical
	Neural network	Artificial neural network	Continuous and categorical

S2.1 Classification tree analysis

Classification tree analysis (CTA) partition the data into separate homogenous groups based on the dependent variable. The two groups where the response variable exhibit the largest homogeneity are chosen by use of the explanatory variable. The recursive partition of the data in this method results in a tree-like structure (Valavanis *et al*. 2008).

Several build-on and varieties exist of this method. Boosted regression trees (BRT) add a boosting algorithm to the individual classification tree produced and can be combined with linear regression from traditional statistics (Torres *et al*. 2015). Through iteration, the algorithm re-weigh the data to optimize cases less well predicted by the previous classification tree and thereby develop a final model. This enable BRTs to handle outliers, missing data, fit interactions between predictors and include different predictor types, even irrelevant predictors (BCCVL 2019; Torres *et al*. 2015; Valavanis *et al*. 2008).

S2.2 Random forest

Random forest (RF) is another approach to classification and regression using the decision tree model concept (Howard *et al*. 2014). Data can be as presence-absence or abundance. RF incorporate a machine learning technique using bootstrap classification and the classification regression tree method (BCCVL 2019; Howard *et al*. 2014).

S2.3 Multivariate adaptive regression splines

Multivariate adaptive regression splines (MARS) use piecewise linear fits of the data whereby smoothening can be avoided. The idea is that by dividing the linear fits into pieces (splines), non-linear responses can be fitted to the data in a regression-based manner for each spline (BCCVL 2019; Valavanis *et al*. 2008).

S2.4 Flexible discriminant analysis

Flexible discriminant analysis (FDA) use several linear models and score their output to the response variable to optimize the fit of the data to linear regression. The idea is to model the differences between data classes and use the modelled combinations as a linear classifiers to best explain the data (BCCVL 2019; Hastie *et al*. 1994).

S2.5 Generalized additive models

Generalized additive models (GAMs) are extensions of linear models that enable smoothing functions to substitute linear and parametric terms otherwise used in Generalized Linear Models (GLMs) (Elith and Leathwick 2009; Valavanis *et al*. 2008). Several varieties exist for both GLM and GAM. For instance Generalized Regression Analysis and Spatial Prediction (GRASP) where GAM is used for spatial prediction and cross-validation, limited absence, weighted absence, predictors accounting and/or factor variables are used to improve model selection, account for spatial autocorrelation and account for possible interactions among predictors (Valavanis *et al*. 2008). Overall, GAMs function well for modelling the linkages between environmental factors and species (Ciannelli *et al*. 2008).

S2.6 Generalized linear models

Generalized linear models (GLMs) are extensions of linear regression models (Valavanis *et al*. 2008). Regression based models for spatial distribution link a given event, such as species occurrence or abundance, to spatial and or environmental data based on a linear relationship (Howard *et al*. 2014; Potts and Elith 2006). For abundance data, the simplest approach is the standard Poisson regression which can be used for count data (Potts and Elith 2006; Valavanis *et* *al*. 2008), whereas the binomial distribution is better suited for binary and proportional data (Valavanis *et al*. 2008). Finally, the negative binomial distribution is well suited to account for over-dispersion which is a common issue that arise when the variance for a given dataset exceeds the mean (Cox 1983; Potts and Elith 2006; Valavanis *et al*. 2008). However, the negative binomial model is not well suited for the type of over-dispersion that derives from zero-inflated datasets (Potts and Elith 2006), which is a common issue for fishery dependent data because of several factors such as fish schooling, aggregation at specific bathymetric features such as water temperature and depth, as well as the non-random spatial targeting of fishing vessels (Ciannelli *et al*. 2008; Kristensen *et al*. 2014; Sims *et al*. 2008).

S2.7 Generalized boosting models

Generalized boosting models (GBMs) are similar to boosting regression trees (BRTs). The concept in boosting is to add small modification parts of a model by repeatedly fitting models or regression trees and emphasize which modifications lead to a better data fit. A new subset of all data is made after each repeated test of model fit to data. The new data subset is random, but input data which the previous model fitted poorly has a higher probability of being selected. This, model accuracy is improved by repeatedly "learning" from the previous model error again and again (BCCVL 2019; Elith *et al*. 2006; Friedman *et al*. 2000; Torres *et al*. 2015).

S2.8 Surface range envelope

Surface range envelope (SRE) use environmental spatial information together with presence-data for species to create likely area where a species can be found. The "envelope" is used as a term to define the minimum and maximum environmental factor values available for the presence-data. Modelling is performed using the computer simulation technique provided by genetic algorithm for rule set production (GARP) which use the envelope values and species presence data to model the potential distribution of the species. Therefore, any area within the range of the envelope values and simulated as suitable using GARP will be included in the potential species range. Envelope values can be reduced, for instance to account for outliers or empirical knowledge, if these account for mismatch between the realized distribution of the species compared to the potential distribution calculated by the SRE (Araujo and Peterson 2012; BCCVL 2019; Guisan and Thuiller 2005; Stockwell and Peters 1999).

S2.9 Maximum entropy

Maximum entropy (MaxEnt) list presence-data for species and environmental factors and derive the widest possible distribution based on these observed presences compared to the limits derived from the environmental factors within a predefined study area. MaxEnt use machine learning to build multiple models and run iterations to optimize model fit. The model concept is overall governed by two main components: i) Entropy, which is used to fit the model to the widest possible species distribution within the study area. ii) Constraints, which is used to limit the predicted distribution based on the environmental factors in order to aim at fitting model to realized rather than potential distribution of the species (BCCVL 2019; Merow *et al*. 2013; Phillips *et al*. 2006).

S2.10 Artificial neural network

Artificial neural networks (ANNs) are non-linear general function approximations that consist of thousands of artificial neurons connected to each other, mimicking the neurons in the human brain (Valavanis *et al*. 2008). Rather than programming a model, machine learning techniques like ANN are fed with example data which specify the correct output. The ANN then create an algorithm that will provide the correct output from input based on the example data. ANN are derived from logistic regression models and share commonalities in their basic structure. But the adaptive or learning aspect of ANNs does not only allow for non-linear approximations making ANNs very flexible and able to handle a large variety of complex data, including cases where data relationships are unknown (Dreiseitl and Ohno-machado 2003; Valavanis *et al*. 2008). However, because of the flexibility of ANN, they are more prone to overfitting than regression methods (Dreiseitl and Ohno-machado 2003).

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Correction sheet

Page	Thesis text	Correction
Page 30. Sea-packing data and SIF	“Principle machinery is presented in Fig. 4. Weighing is done in kilogram with dynamic scales at 2-digit precision. The grading machine software prints labels”	Should read: …with dynamic scales at 2 decimal place precision.
Box 3.2. Making of paper II	”A linear model was used for this as the agreement should be 1 in the perfect world. Additionally, an”	Should read: ….should be 1:1 in the perfect world.