Steam-powered winch on board a fishing vessel. After Lübbert in Schnakenbeck 1953

SHIRE

Historical reconstruction of the Wadden Sea fish assemblage – Swimway historical reference

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Summary

The trilateral Wadden Sea is a highly dynamic area, providing shelter from predators and rich feeding grounds for a host of fish species. In recent decades the Trilateral area of the Wadden Sea has gained much attention in terms of its importance for fauna and the conservation of the area. Present long-term data sets used for determining conservation strategies and targets only go back as far as 1960, a period in which the area was already under intense anthropogenic pressure. To be able to set realistic targets for conservation strategies aimed at pre-defined objectives such as the trilateral fish-targets (EG-Swimway, 2021), additional data is required that goes further back in time. Using the PRISMA approach for conducting a systematic review, the present study aimed to fill in this gap by providing a database on fish assemblages in the Wadden Sea between 1500-1970. In total 4240 individual records were screened of which 109 were eventually included in the synthesis. With data on the historical occurrence of 148 species of fish the present database has laid the foundation of a significant informative framework on historic fish assemblages in the Wadden Sea that could be used as a starting point for future conservation efforts.

Zusammenfassung

Das trilaterale Wattenmeer ist ein äußerst dynamisches Gebiet, das einer Vielzahl von Fischarten Schutz vor Raubtieren und reiche Nahrungsgründe bietet. In den letzten Jahrzehnten hat das trilaterale Wattenmeer hinsichtlich seiner Bedeutung für die Fauna und die Erhaltung des Gebietes viel Aufmerksamkeit erregt. Die derzeitigen Langzeitdaten, die für die Festlegung von Erhaltungsstrategien und -zielen verwendet werden, reichen nur bis 1960 zurück, einem Zeitraum, in dem das Gebiet bereits unter starkem anthropogenem Druck stand. Um realistische Ziele für Erhaltungsstrategien festzulegen, die auf vordefinierte Ziele wie die trilateralen Fischziele (EG-Swimway, 2021) ausgerichtet sind, sind zusätzliche Daten erforderlich, die weiter zurückreichen. Mit Hilfe des PRISMA-Ansatzes für die Durchführung einer systematischen Übersichtsarbeit wollte die vorliegende Studie diese Lücke schließen, indem sie eine Datenbank über Fischbestände im Wattenmeer zwischen 1500 und 1970 bereitstellt. Insgesamt wurden 4240 Einzelbelege gesichtet, von denen schließlich 109 in die Synthese aufgenommen wurden. Mit Daten über das historische Vorkommen von 148 Fischarten hat die vorliegende Datenbank den Grundstein für einen aussagekräftigen Rahmen über historische Fischbestände im Wattenmeer gelegt, der als Ausgangspunkt für künftige Schutzbemühungen dienen kann.

Sammenfatning

Vadehavet er et meget dynamisk område, der giver beskyttelse mod rovdyr og er et rigt fødeområde for mange fiskearter. I de seneste årtier, har det trilaterale område af Vadehavet fået stor opmærksomhed i forhold til betydningen for faunaen og bevarelsen af området. De nuværende langsigtede datasæt, der anvendes til at fastlægge bevaringsstrategier og -mål, går kun tilbage til 1960, en periode hvor området allerede var under intensivt menneskeskabt pres. For at kunne opstille realistiske mål for bevarelsesstrategier, der er rettet mod foruddefinerede mål som f.eks. de trilaterale fiskemål (EG-Swimway, 2021), er der behov for yderligere data, der går længere tilbage i tiden. PRISMA-metoden til gennemførelse af en systematisk gennemgang var anvendte at undersøge og udfylde dette tomrum ved at tilvejebringe en database over fiske arter og deres hyppighed i Vadehavet i perioden 1500-1970. I alt blev 4240 individuelle registreringer screenet, hvoraf 109 i sidste ende blev medtaget i syntesen. Med data om den historiske forekomst af 148 fiskearter, har den foreliggende database lagt grunden til en betydelig informativ ramme om historiske forkomst og økologi af fisk i Vadehavet, som kan bruges som udgangspunkt for fremtidige bevarings og forvaltning beslutninger.

Samenvatting

De trilaterale Waddenzee is een zeer dynamisch gebied, dat beschutting biedt tegen roofdieren en rijke voedselgronden biedt aan een groot aantal vissoorten. De laatste decennia heeft het trilaterale gebied van de Waddenzee veel aandacht gekregen wat betreft haar belang voor de fauna en het behoud van het gebied. De huidige langetermijngegevens die worden gebruikt voor het bepalen van instandhoudingsstrategieën en -doelstellingen gaan slechts terug tot 1960, een periode waarin het gebied reeds onder zware antropogene druk stond. Om realistische doelen te kunnen vaststellen voor instandhoudingsstrategieën gericht op vooraf bepaalde doelstellingen, zoals de trilaterale visdoelen (EG-Swimway, 2021), zijn aanvullende gegevens nodig die verder teruggaan in de tijd. Door gebruik te maken van de PRISMA-aanpak voor het uitvoeren van een systematische review, wilde de huidige studie deze leemte opvullen door een database over vispopulaties in de Waddenzee tussen 1500-1970 aan te leggen. In totaal werden 4240 individuele records gescreend, waarvan er uiteindelijk 109 in de synthese werden opgenomen. Met gegevens over het historisch voorkomen van 148 vissoorten heeft deze databank de basis gelegd voor een belangrijk informatief kader over historische vispopulaties in de Waddenzee dat als uitgangspunt kan dienen voor toekomstige beschermingsinspanningen.

Contents

Introduction

Biological background

In an ecological context, the term "history" often refers to completing the life cycle in an ontogenetic sense. In fish, for example, adults mate and spawn, larvae hatch from eggs and endure the transition from internal (yolk sac) to external (foraging) food acquisition. An immense mortality of up to 99 percent is typical for these early life stages, regulating much of the entire population dynamics of fish and other r-strategists (Houde, 2008, 2016; Houde et al. 2022). Survivors of the mass mortality during early life stages metamorphose into pigmented juveniles seeking coastal estuarine areas such as the Wadden Sea, where they translate high temperatures and rich food supply to fast growth, through which they eventually become too big to be eaten by predators (Harden Jones, 1968; Gislason *et al.*, 2010). At the juvenile stage, predation mortality is still enormous, yet much lower already than for eggs and larvae. Upon sexual maturity, individuals seek and find mating partners, which practically happens by females releasing their spawn into the water where males are waiting to release their sperm to inseminate the eggs. Organisms such as fish have evolved life history traits (size at birth, growth pattern, age and size at maturity, number, size and sex ratio of offspring, age- and size-specific reproductive investment and mortality, and life span) that combine to affect fitness in the sense as to complete the life cycle (Stearns 1992). Success or failure of individuals to do so directly affect demographic rates at the population level. In the recent past, however, anthropogenic activities have increased dramatically in importance both as forces modifying life history traits and as factors affecting fish life cycles. Due to their central position in the food web as predator and prey (Fauchald *et al.*, 2011; Dänhardt *et al.*, 2018), fish provide multiple regulating ecosystem services and many ecosystem functions (e. g. Helfman, 2007; Audzijonyte & Kuparinen, 2016; Villéger *et al.*, 2017; Tulp *et al.*, 2022). In addition to the transfer of nutrients and energy - both within the aquatic system and between terrestrial and aquatic ecosystems (Friese *et al.*, 2018) - fish contribute to the maintenance of genetic, species and ecosystem diversity as well as to the diversity of biological interactions. Thus, they play a central role in the North Sea ecosystem and interact with almost all other groups of organisms (Dänhardt *et al.*, 2017).

The world's largest intertidal wetland, the Wadden Sea in the south-eastern North Sea, hosts more than 120 fish species (Berg, 1996; Tulp *et al.*, 2022), most of which spend only part of their life cycle in the area that is protected as national park and UNESCO World Heritage site (Schmäing & Grotjohann, 2021). Here, the life cycles of numerous marine and estuarine fish and two lamprey species overlap, providing shelter from predators and rich feeding grounds for a host of fish species (flatfish, groundfish and pelagic fish) and their different life stages

(Elliot *et al.*, 2007; Tulp *et al.*, 2017a, 2022). According to their life style and the function the Wadden Sea fulfils in their life cycle, fish occurring here can be classified as marine pelagic juveniles (e. g. Atlantic herring *Clupea harengus*), demersal marine juveniles (e. g. European plaice *Pleuronectes platessa*), diadromous species (e. g. European smelt *Osmerus eperlanus*), marine adventitious (e. g. tope shark *Galeorhinus galeus*), and Wadden Sea residents (e. g. European eelpout *Zoarces viviparus*) (Swimway, 2019; Tulp *et al.*, 2022).
The Wadden Sea Plan (CWSS 2010) defines conservation targets for fish, all making more or less direct reference to life cycles. As a consequence, these targets have been proposed to be specified and related to the overall target, that "there should be no human-induced bottlenecks in the Wadden Sea for fish populations or their ecosystem functions" (Tulp *et al.*, 2017a, 2022). However, conservation objectives such as the trilateral fish-targets (CWSS 2010) require some sort of reference or baseline, for which even the longest contemporary monitoring data going as far back as 1960 (Van Walraven *et al.*, 2017) only started when the area was already under widespread anthropogenic pressure, and which are, thus, still too short. This does not mean that the historical situation is to be used as an actual target for restoration, but rather that it can highlight the conditions for successful restoration measures (Kittinger *et al.*, 2015). In attempt to bridge the gap between data that have been collected by means of quantitative and standardized monitoring and anecdotal data ranging as far back as history records permit (Roberts, 2007; Estrella-Martinez *et al.,* 2019), the national red lists also incorporate historical data to assess the establishment and population trends of species in national marine waters, the coastal waters and estuaries to derive intermediate to long-term trends of abundance and occurrence of fish in the area under investigation (Thiel et al. 2013 and citations therein). These include old literature (e. g. Möbius & Heincke, 1883; Heincke, 1894, 1896; Ehrenbaum, 1927, 1936; Schnakenbeck, 1928, 1953; Duncker & Ladiges, 1960), as well as data from museum collections (Thiel *et al.*, 2009).
The dynamics that characterize the area arise from a complex interplay between hydrographic and hydrological factors (Reuter *et al.*, 2009) and are strongly influenced by tide and climate (De Jonge *et al.*, 1993). However, since the early 1600s these dynamics have been impacted by human activities, including sand extraction, fisheries, and the discharge of nitrogenic and phosphorous compounds (Wolff, 2000; Lotze *et al.,* 2005). Habitat loss for fish occurred also due to large scale land reclamation such as the closure of the Zuiderzee in 1932, the Lauwerszee in 1969, or the large-scale reclamations of tidal marshes along the German coast from 1951 to 1991 (Goeldner, 1999). All these activities have most likely affected the fish assemblages in the area (Wolff, 2000; Lotze, 2007; Holm, 2005), although the actual impact is unclear for most species. As a consequence, taking the historical perspective has been identified as a clear research focus in the years to come during the first Wadden Sea SWIMWAY conference held in Hamburg in September 2019 (Dänhardt, 2019).
While historical information is valuable to define targets where conservation and

development should be heading, knowledge and a sound process understanding on former occurrence and abundance of species and habitats will also be crucial to address the shifting baselines phenomenon (Pauly, 1995; Jackson *et al.*, 2001; Bom *et al.*, 2020).

Shifting baselines

> *"We do not have to look too deeply into the history books, into contemporary accounts, for scenes dramatically different to our own normal. Yet we live in denial of these catastrophic losses. Our ideas about species can be misleading, when our observations are made in a landscape depleted of habitat options." Isabella Tree (2018), Wilding*

In his seminal one-pager, Daniel Pauly (1995) described an omnipresent psychological and sociological phenomenon that has far-reaching consequences for contemporary conservation theory and practice. The shifting baseline syndrome defines the circumstance, that in the absence of past information or experience with historical conditions, members of each new generation accept the situation in which they were raised as being normal. The shifting baseline syndrome is increasingly recognized as one of the fundamental obstacles to addressing a wide range of today's global environmental issues (Soga & Gaston, 2018), and even though contemporary baselines exist, e. g. as catch quota (e. g. Morgan, 1997), EcoQs (e. g. Greenstreet *et al.*, 2006) and guiding principles (e. g. Pezenburg *et al.*, 2002), baselines tend to encourage pre-baseline amnesia. Symptoms include looking at a seascape and seeing, what's there, not what is missing, and the pressure for authors of academic papers to reference primarily contemporary research. As a second and often overlooked statement, Pauly (1995) claimed that anecdotes may be as valuable as quantitative information of species occurrence, and that anecdotal evidence is just another type of data useful to reconstruct the historical past of species, communities and ecosystems (see also Mowat, 1984; Jackson *et al.*, 2001; Roberts, 2007; Kittinger *et al.*, 2015; Thurstan, 2022; Estes & Vermeij, 2022). Big changes happened long ago, and only combining information noted by successive generations will allow a full appreciation of the change in fish diversity that has occurred in the sea, among others things as a result of human activity. The quality of historical data notwithstanding, historical events and developments have profoundly affected the composition, distribution, and abundances of species in contemporary ecosystems, requiring to take history into account to understand how ecosystems work and change (Estes & Vermeij 2022). Getting an idea about past species composition and occurrence by incorporating anecdotes (=earlier knowledge) into the present conservation and management schemes would also bring fishes into the biodiversity debate, whose evolution and ecology have probably been impacted by human activity more severely than in any other group of vertebrates (Pauly 1995). The utility of recovering past knowledge and using it for contemporary conservation seems obvious: preventing a shift in baselines (Pauly 2001).

Wadden Sea fish conservation and SWIMWAY vision & work programme

The framework for fish conservation in the Wadden Sea is represented by generic conservation objectives for fish - the so-called Trilateral Fish Targets (CWSS, 2010):

1. Viable stocks of populations and a natural reproduction of typical Wadden Sea fish species;
2. Occurrence and abundance of fish species according to the natural dynamics in (a)biotic conditions;
3. Favourable living conditions for endangered fish species;
4. Maintenance of the diversity of natural habitats to provide substratum for spawning and nursery functions for juvenile fish;
5. Maintaining and restoring the possibilities for the passage of migrating fish between the Wadden Sea and inland waters.

These objectives are broadly formulated to make them widely agreeable. For their implementation, they need further specification and, on the way, to measure progress towards their implementation. Current knowledge is sufficient to start protecting fish in the Wadden Sea immediately, while at the same time, a lack of basic understanding on the functioning of the Wadden Sea system for fish prohibits operationalizing the Fish Targets of the Wadden Sea Plan (Tulp *et al*., 2017a). Consequently, a parallel process is needed, in which complementary strings of activity inform and promote each other. Using best available knowledge, dedicated fish conservation measures need to be implemented now and optimized based on effective monitoring, which yields the necessary feedback to develop best-available practice. At the same time, research focussed on processes relevant for conservation needs to be carried out and clearly communicated to ensure the integration of the results into conservation action, with systematic input of knowledge requirements from the conservation measures (Dänhardt, 2019).
The Wadden Sea SWIMWAY vision and action programme has been developed to operationalize the Fish Targets of the Wadden Sea Plan 2010 by deriving concrete courses of action to guide the implementation of programmes dedicated to approaching the approved targets. These fields of action, the so-called pillars, are research and monitoring, policy, measures, stakeholder involvement, and communication and education (SWIMWAY, 2019).

For each one of these pillars, historical data on the occurrence of particular fish species may provide valuable or even essential information for defining and pursuing realistic targets for management action, both with respect to existing conservation goals or with respect to defining or revising conservation goals. Although much of the historical data from before 1850 are from fisheries records, marine historical ecology can inform us about what the populations of a focal group of organisms, such as fish, have been in the past, and under which conditions these populations could flourish so we can start helping them to do so and apply suitable conservation measures (Pauly, 2013; Thurstan, 2022). For all of these pillars, historical data can yield relevant information, e. g. on the decline and recovery of endangered species (Thurstan *et al.*, 2010; Kittinger *et al.*, 2015 and references therein), on the conservation of fisheries resources, on restoring ecosystems, and engaging the public (Kittinger *et al.*, 2015 and references therein). These concepts have previously been described and required for the Wadden Sea (e. g. Lotze *et al.*, 2005a, 2005b, 2007; Holm, 2005; Wolff; 2000). Yet, this approach has never been applied to fish and their specific roles and functions in the ecosystem.

Project scope

Correctly identifying the ecological past is clearly fundamental to considering how conservation should proceed in the future. Creating a sound image on former species assemblages, requires historical data on the former occurrence, abundance, and the use of habitat of species as early as possible relative to the period of human intervention. Ultimately, to understand how these parameters have changed over time, such a reference should also identify potential drivers of change in these assemblages through anthropogenic as well as natural pressures. Collecting this information in a single database would not only aid in elucidating the changes that different populations experienced throughout their history but could also be vital in evaluating the achievability of future conservation or restoration incentives (Caswell et al. 2020).

In pursuit of the ultimate aim of a historical reconstruction of the Wadden Sea fish assemblage in order to support contemporary targets and future action for conservation and management, the present pilot project Historical reconstruction of the Wadden Sea fish assemblage – Swimway historical reference - SHIRE - was intended to take first steps in this direction. The participation of Dutch, Danish and German colleagues with SHIRE was intended to expand the search to historical sources written in English, Dutch, Danish and German.

This project was NOT about an exhaustive species-by-species analysis of all historical sources on fish in the Wadden Sea, it was NOT about producing a template how to use historical data for fish conservation the Wadden Sea, and it was NOT about establishing ultimate stressor-receptor-relationships that can be directly translated to the contemporary state of the ecosystem. Instead, this project was about scanning the field of potential historical sources of information to the end outlined above. It was about testing and developing the method of systematically reviewing the literature, both digital and non-digital, primary and grey literature, and it was about developing recommendations on how historical data might be used to supplement contemporary information. These objectives should serve as a starting point for future activities sufficiently equipped with the resources to come up with a full historical reconstruction of the fish community in the Wadden Sea when human intervention was a fraction of what it is now, as a guide for contemporary fish conservation in the Wadden Sea. Such knowledge at the species level is one crucial element of eventually formulating and implementing effective fish conservation in the Wadden Sea, and to ultimately minimise any anthropogenic bottlenecks for fish life cycles in the Wadden Sea (see above and Tulp et al. 2017a).

The overall objective of SHIRE was a contribution to a reference on the fish community in the Wadden Sea before human intervention. In retrospect this is not possible as the area has been under constant change for the past centuries with diking and land reclamation occurring already well before the 1500s (Reise, 2013). Based on the available information, an overview of fish present in the Wadden Sea from as far back in time as possible to the present, by means of electronic, museum, fisheries agencies and other sources, from Denmark, Germany and the Netherlands was to be developed. The outcome of this activity is a preliminary and partial overview of fish species present in the Wadden Sea from as far back in time as possible to the present and perhaps more importantly a framework and list of possible additional sources to support a future, comprehensive undertaking.
A systematic review approach (Aromataris, 2014) was utilized to identify a substantial number of records originating from digital and analogue sources found in the Netherlands, Germany and Denmark. Through the systematic collection of as much data as possible this project aimed to develop the framework of a dataset of fish assemblages between 1500 and 1970, which in turn, could be used to inform future conservation and management efforts (Caswell *et al.*, 2020). Besides collecting as much data as possible on species occurring in the Wadden Sea as far back as possible, the review also aimed to uncover information on the habitats used by the species present in the area along with the drivers that could be held responsible for any changes in the species composition. Identifying the historic drivers, anthropogenic, natural, or both, could prove to be vital for the recovery of species or habitats when evaluating whether changes could be mitigated. Questions guiding the systematic review of digital and non-digital literature included the following:

- Which species was the Wadden Sea fish community composed of in historical times?
- Which have disappeared, which were added, which have reappeared?
- What was the absolute and relative (dominance) abundance of the single species?

- What where the reasons for disappearance, appearance, reappearance and change in dominance structure?
- Can they be influenced and how?
- Did habitat dynamics and species-habitat relationships play a role?

The results of SHIRE will serve as pre-study and template for the integration of additional sources to complete the assessment, and will also serve as basis for a potential trilateral Swimway project (see below), especially with respect to the lessons learned during the systematic literature review, e. g. how did the systematic review approach work with electronic sources compared to non-digital sources? What worked well, what did not work?

Systematic Review

Methods

The present study used a systematic review including the PRISMA approach (Moher *et al.*, 2009) for a transparent and repeatable identification of records. This type of review, inspired by a study by Bastardie and Brown (Bastardie & Brown *et al.*, 2021) and ongoing work in the Horzion 2020 project SEAwise, was chosen based on the capability of efficiently acquiring and merging as much information as possible into one synthesis (O'Dea *et al.*, 2021). Those characteristics were vital for this study since the number of records yielded through literature searches, related to 'fish* AND Wadden Sea' would otherwise be unmanageable. The process of the systematic review was defined by five consecutive stages (Figure 1). Starting with the scoping phase and followed by the searching, screening, extracting, and analyzing phase.

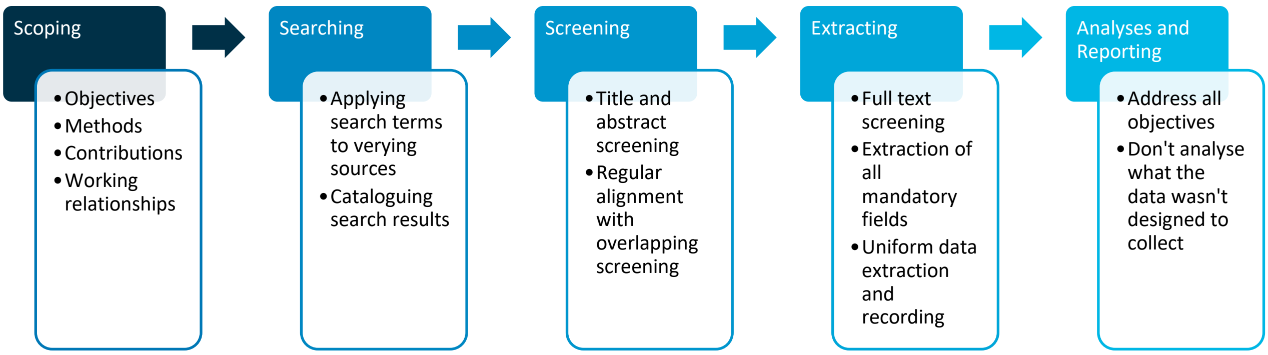

Figure 1. All steps of the systematic review summarized (Brown, 2022).

Scoping

The process started with the scoping phase in which the objectives and the methods of the review were carefully set out. Setting out the objectives required defining the study period and region of interest. The start of the study period 1500-1970 was chosen based on the end of the Middle Ages, coinciding with the start of written documentation (1500 A.D.), while the end of the period was chosen based on the onset of standardized monitoring projects, such as the QSR (Quality Status Report) beam trawl monitoring program in 1970 (Tulp *et al.,* 2017a). The study area used in this review ranged from the city Den Helder in the Western Dutch Wadden Sea all the way up to Blavandshuk, Skallingen in Denmark including all of the inlets and coastal waters of the adjacent barrier islands. The study region also included all the estuaries linked to the latter area, such as the Ems and Elbe along with former parts of the region that have been closed off such as the former Zuiderzee and Lauwerszee. Since the species of interest also included diadromous species known to travel up rivers such as cod, salmon and sturgeon, an exception was made for findings of these species outside the designated area but within neighboring ICES rectangles or connected streams/rivers. ICES rectangles are based on a longitudinal and latitudinal grid created for a simplified analyzation and visualization of data.

With the study period and region defined, the main objective of the systematic review was to establish a reference on fish assemblages in the Wadden Sea between 1500 and 1970, along with the side-objective of identifying the anthropogenic and natural drivers of change in fish assemblages.

This systematic review differed from the average review due to the use of many analogue sources in contrast to relying solely on digital sources such as Web of Science (WoS). Using analogue sources as potential databases was deemed a necessity in order to find new information on the subject, especially in the period before the onset of monitoring projects where information on species occurrence was scarce. The analogue sources that were identified for this review included libraries, museums, and archives of each of the trilateral countries. For logistical reasons, primarily time constraints, a selection was made from the list of the analogue sources to be reviewed. The full list of potential sources including the selection that was used for this review can be found in the Annex I.

Defining wide but clear and unbiased search term was essential in capturing the scope of the objectives. Since it was impossible to systematically search for information that only related the period between 1500 and 1970 the search terms were only made up out of two elements. The first element being the topic of interest combined with the second element being a location of interest. As for the first element, the search term fish* alone did not cover the full scope of the search. Since fish assemblages also include types of fish that could be referred to by different names such as sharks, rays, skates, and lampreys, it required these to be added to the list of search terms. As for the second element searching for the Wadden Sea alone would exclude any records using more precise locations/areas, these locations could be added to list of search terms depending on the origin of the source.

The search query for digital sources was defined by a combination of search terms of both elements (Table 1). For instance, in the case of a digital source such as Web of Science, the search was conducted by searching in abstract and title for: ‘(Fish* OR rays OR skates OR sharks OR lampreys) AND (Wadden sea OR German Bight OR Southern North Sea OR Zuiderzee)’.

Search terms used for digital sources regarding the type of species were kept simple as including all species and taxonomic names would generate too many results and could potentially bias the outcome. The search terms regarding the location were instead more elaborate to widen the search grid for potential data.

Records found in analogue sources differed from records derived from digital sources in the sense that these typically were written in either Dutch, German or Danish and made use of the names of cities and/or countries/provinces in their titles. This combined with the inability of search engines to search in abstracts (or summaries) required more freedom in choosing search terms for specific analogue sources.

Table 1. Pre-determined search terms used for searching in both digital and analogue sources.

	1st element	2nd element
Search terms for digital sources	Fish* OR rays OR skates OR sharks OR lampreys	Wadden sea OR German Bight OR Southern North Sea OR Zuiderzee
Search terms for analogue sources	Visschen OR Vis* OR dieren OR fauna OR fish* OR rays OR skates OR sharks Or Fisk OR Haj OR Rochen OR Fisch OR Hai	Wadden OR Groningen OR Friesland OR Zuiderzee OR Frisia OR wattenmeer OR Vadehav OR Mandø OR Rømø OR Fanø OR Danmark

Searching

The next step was the searching phase, in this phase the previously determined search terms (Table 1) were applied in the search engines provided by the previously appointed sources and the resulting search results catalogued.

Screening

In the third phase of the review, the screening phase, all collected material was filtered for duplicates and screened based on title and on abstract. Screening was done using a set of exclusion criteria related to the objectives of the review (Table 2). To ensure no data were missed all types of ecological, archeological, historical and fishery records were deemed admissible if not excluded based on the exclusion criteria.

Table 2. Exclusion criteria used for screening the titles, abstracts and full texts of catalogued records.

Reason	Definition
A	Non-fish or driver related
B	Information not related to 1500-1970
C	Information not related to Wadden sea area
D	Information hearsay or thirdhand
E	Reviews on already included data

Extracting

When all irrelevant material was filtered out, the records that were left over moved on to the extraction phase in which they underwent full text screening. This part of the review included the extraction of data from the records in uniformed fashion. Information contained in a record was required to meet specific criteria to be included in the synthesis. Regardless of the origin of the information embedded in a record, the author of the record was required to have specified the location, the species or family of fish and the year of an observation, unless the record was written in the present tense and the publication dated before 1970, for it to be extracted.

Once data was found that met the requirements of extraction it could be transferred to the extraction scheme based on a study by Jackson (Jackson *et al.*, 2001). Data in this scheme is sorted by the common name of the species of interest, or in case no specific species was mentioned, by family name (e.g., salmon, cod, sturgeon). The rest of the scheme is then divided by a set of required and additional data. The required data include information on the functional guild of the species, the location in the Wadden Sea mentioned in the record, the occurrence of the species, the historical period related to the observation of a species mentioned in the record or when no time was mentioned the year of publishing, along with the name of the person responsible for the extraction and a reference related to that specific record. Additional information that was mentioned in a record could vary substantially in nature, therefore the scheme included columns named 'proxy2' and 'proxy3' (Figure 2). A proxy represented any kind of explanatory variable where 'Proxy2' corresponded with 'Estimate or observation2' representing any information of quantitative nature whereas 'Proxy3' corresponded with 'Estimate or observation3' and represented information of qualitative nature. The use of proxies allowed for the extraction of anything deemed important, such as the observational abundance, catch amount, size, life stage, etc. Furthermore, the additional data included information on the drivers of change, anthropogenic or natural, type of data to keep track of previously used survey data and a comment section for anything else that needed to be mentioned.

Common name	Taxonomic name	Functional group	Location	Ext
Allis shad	Alosa alosa	Diadromous species	Dutch, German wadden sea	Nils

Proxy1	Proxy2	Proxy3	Time start	Time en
Presence	Observational abundance		1941	1984

Estimate 1	Estimate or observation 2	Estimate or observation 3
1	extremely rare or absent	

Anthropogenic driv	Natural drive	Type of record	Reference
		Historical ecology	57

Figure 2. Organization of the columns used in the extraction scheme. Data of the Allis shad *used as an example.*

Analyses and reporting

In the final step of the review the results in the form of the identified records and the extraction scheme were evaluated to investigate whether all objectives had been accomplished. This part included an evaluation of the number of identified records along with a review on the amount of extracted data and the contents of the dataset. To illustrate the effectiveness of the systematic review in creating a sound reference on species assemblages throughout the investigated period all collected data on the previously determined flagship species (WG-Swimway, 2021) and that of potentially extinct species was reviewed and used as an example.

Results

Identification of relevant records

A total of 4240 individual records were identified from digital and analogue sources. The majority of these were excluded based on being unrelated to the period between 1500-1970 and/or being unrelated to the Wadden Sea area. Out of the 338 records that were not excluded in any of the previous steps 109 were ultimately included in the synthesis, of which most (79%) originate from analogue sources.

Table 3. Overview on the number of records left over after screening and extraction in the systematic review. Note that "Total" refers to data entries in all records examined, not the total of all records examined (see figure 4).

Step in the screening phase	Number of digital search results	Number of analogue search results	Total
After search	1332	3004	**4336**
After removing duplicates	1332	2908	**4240**
After exclusion by title or abstract	57	281	**338**
Included in the synthesis	23	86	**109**
Pending	4	61	**65**

Extraction scheme

A total of 1130 rows of data were extracted from the records included in the synthesis, mounting to a total of 148 species with data on their historical occurrence in the Wadden Sea (Annex I). All species, except vagrant species, were assigned to one of the functional groups according to the Wadden Sea SWIMWAY action program (EG-SWIMWAY, 2021) and the QSR 2017 (Tulp *et al.*, 2017a). Out of these 1130 rows most data belonged to the pelagic marine juvenile group (22%), closely followed by demersal marine juvenile group (21%) and diadromous species (17%) (Figure 3). In comparison, the functional groups of the marine adventitious and Wadden Sea resident species only comprised 14% and 12%, respectively, of the total data set.

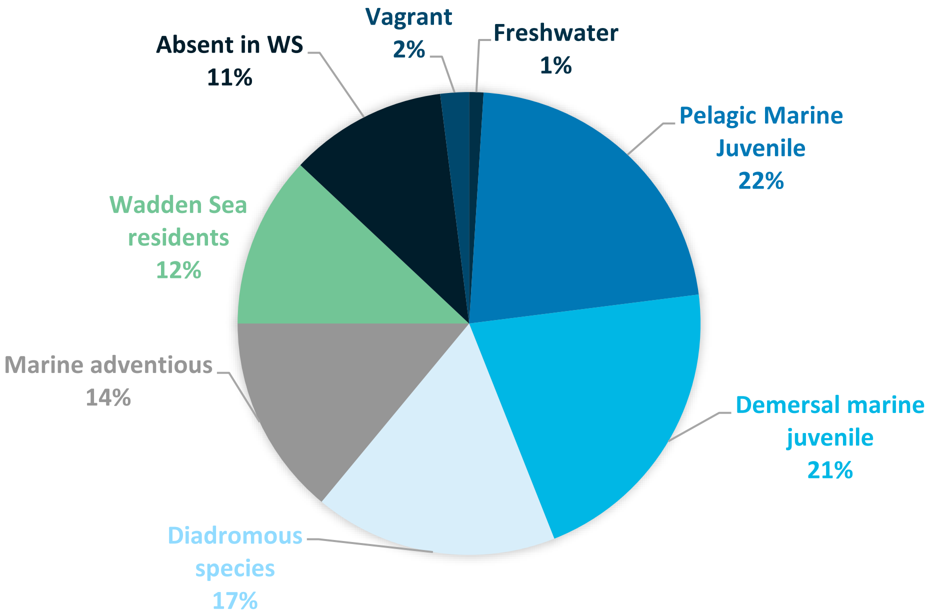

Figure 3. Pie chart showing the distribution of the total dataset (n=x records) in the extraction scheme for each of the functional groups

Records over time

The total amount of data from historical ecology (713 data entries) was greater than the amount of collected fishery data (418 data entries). However, data belonging to the period <1825 consisted predominantly out of historical fishery data (Figure 4). Zooming in on this period revealed the dataset of this period to be comprised of only 27 species which were mostly members of the pelagic marine juvenile, demersal marine juvenile and diadromous species groups (Figure 5) and species with historical commercial interest (Figure 6).

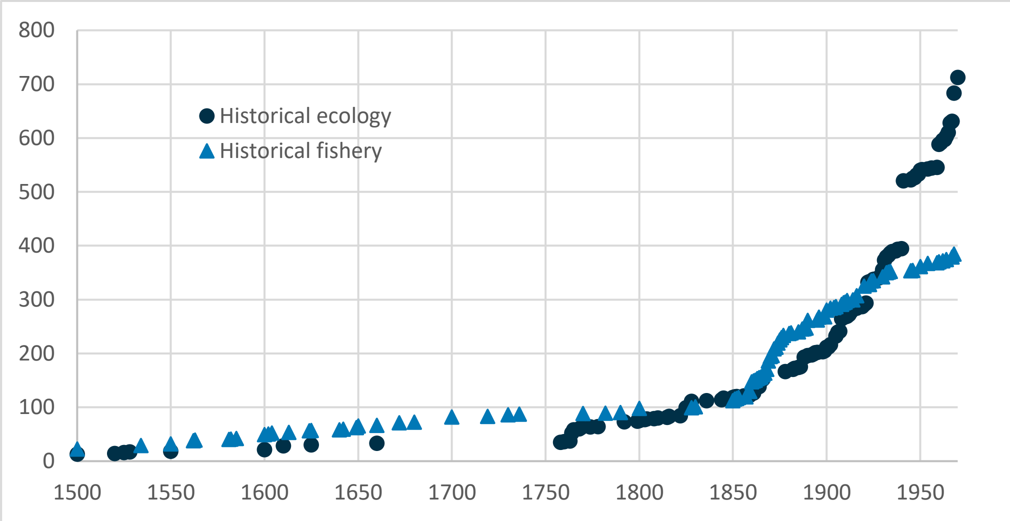

Figure 4. Total sum of fishery and ecology data entries in the database (Y-axis) through time (X-axis).

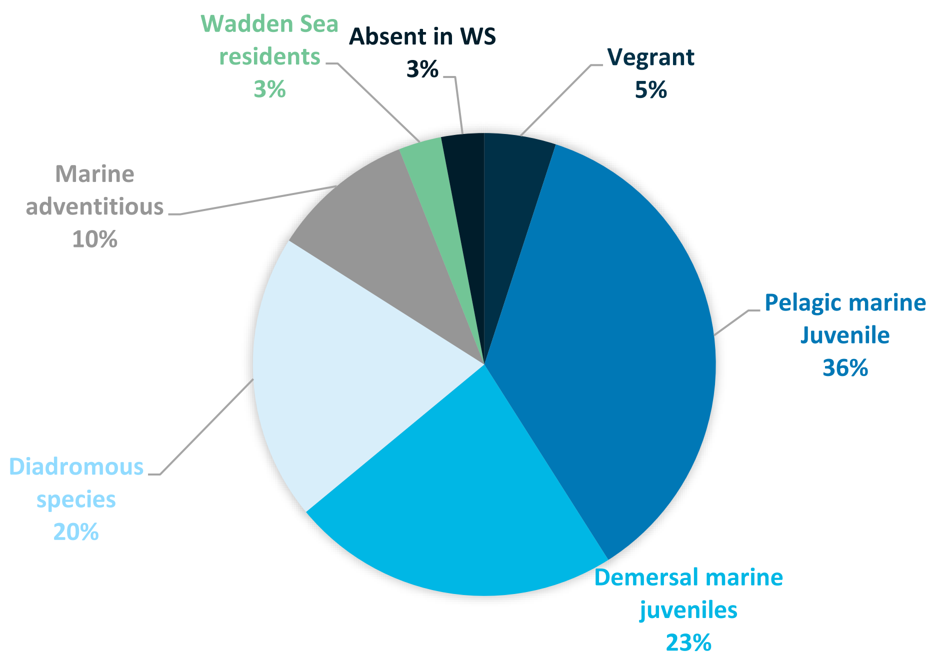

Figure 5. Distribution of the total dataset in the extraction scheme for each of the functional groups before 1825.

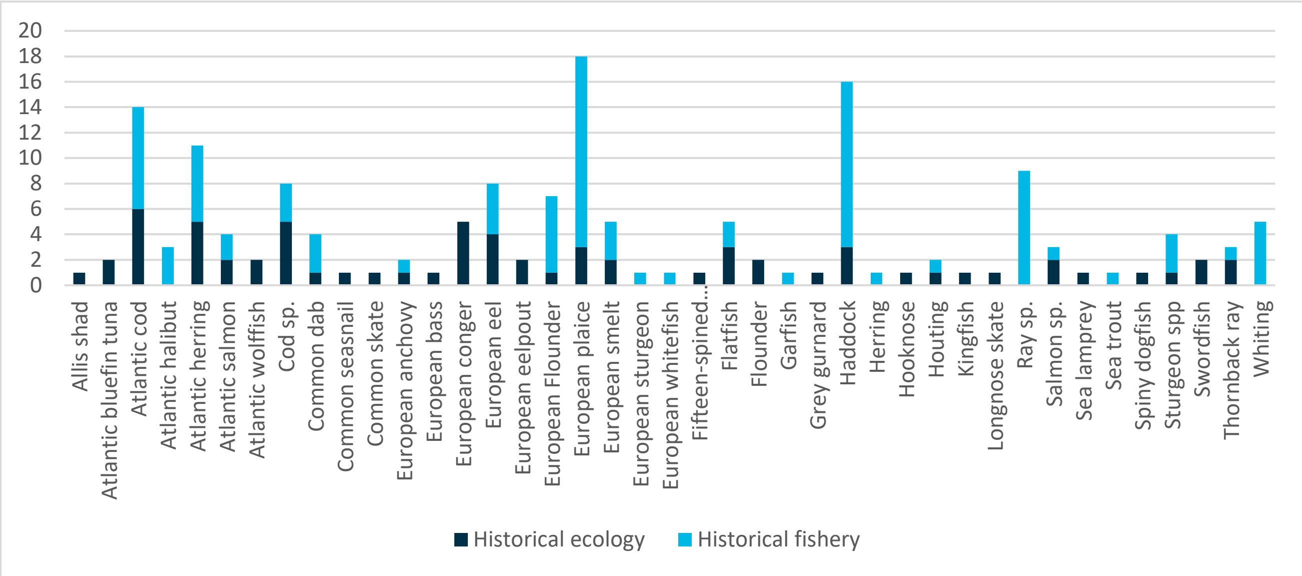

Figure 6. Number of historical fishery and ecology records (Y-axis) for all species with data on their occurrence before 1825.

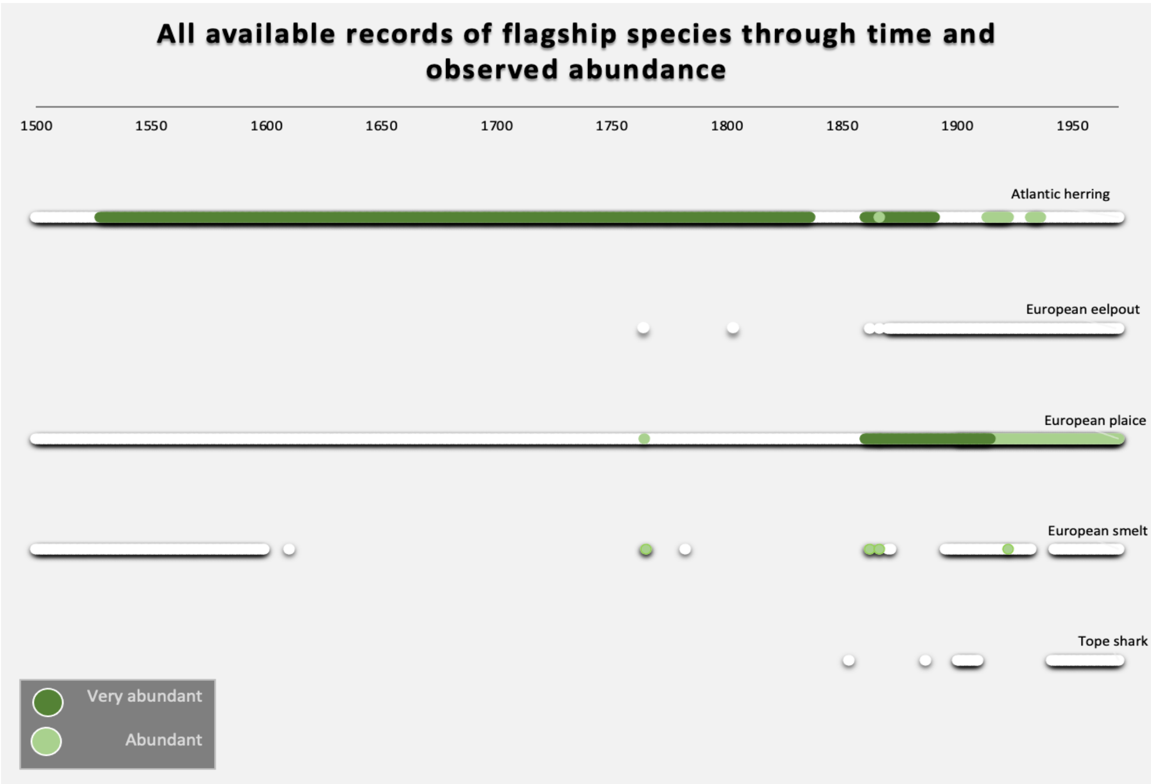

Figure 7. Observed abundance of flagship species between 1500 and 1970.

Flagship species

The total number of data entries along with data on occurrence, observed abundances and drivers regarding the flagship species were evaluated to establish the effectiveness of the systematic review (Figure 7).

Atlantic herring (*Clupea harengus*) The representative of the pelagic marine juvenile group, Atlantic herring, is the most recorded species in the dataset (65 data entries). Based on these records these fish were observed to be very abundant in the period before 1891 (Figure 7), especially in the Zuiderzee, after which they were still observed as an abundant species in the Dutch Wadden Sea until 1936. Until 1970 catch amounts were still reported to be high although Herring stocks in the Dutch Wadden Sea were already being reported to be decreasing in the period of 1930– 1939 as the result of seagrass disappearance (Polte & Asmus, 2006).

European plaice (*Pleuronectes platessa*) From the records in the database (64 rows), it becomes clear that plaice have been around the entire period of 1500-1970 and is one of the few species that is being reported as an observed abundant species in the Wadden Sea in more recent years (Figure 7). However, the number of records reporting on their abundance before 1850 is limited to one report from the former Zuiderzee.

European eelpout (*Zoarces viviparus*) Data collected on the representative species of the Wadden Sea, the European eelpout, was limited (17 rows). The presence of the European eelpout could only be dated back as far as 1764 in the Wadden sea area with limited data on observed abundance and catch statistics (Figure 7). However, the species was observed to be abundant in the Dutch Wadden Sea in both the years 1941 and 1966.

European smelt (*Osmerus eperlanus*) Like the European plaice the dataset (22 rows) shows that the smelt was present throughout the period of 1500-1970, except for a remarkable gap in data between 1611 – 1765 (Figure 7). While this species was never reported as rare, reports of this species being abundant are limited to the period of 1765 - 1922 in the Zuiderzee. For more recent years such records were non-existing, however, catches were reportedly declining in the period of 1946 – 1969 due to an increase in coastal construction.

Tope shark (*Galeorhinus galeus*) Although the tope or school shark is regarded as a flagship species, representing the adventitious group, the amount of collected data on this shark is limited (7 rows) compared to other species from the same functional group (e.g., thornback ray, 19 rows; spiny dogfish, 8). Their presence can only be dated back as far as

1853 in the Dutch Wadden sea (Figure 7), whereas the spiny dogfish was already observed in 1764 (Annex I). Regardless it was the only species of shark that was not observed as being extremely rare in the most recent period.

Possible extinctions

Whereas many records reported a large number of species only being observed on a few occasions while many others were only observed as being rare or extremely rare, a handful of species have been observed to be abundant at first but were reported as being extremely rare or even extinct in the most recent years. For instance, the broadnosed pipefish (*Syngnathus typhle*), which went from being observed as abundant in 1920-22 (Redeke, 1922, 1941) to being rare in 1935-1941 (Redeke, 1941) to being absent in 1935-1970 (De Jonge *et al.,* 1993). According to the data the population was likely reduced through loss of habitat in the form of closure of the Zuiderzee (Redeke, 1941) and the loss of eelgrass in the Wadden Sea (De Jonge *et al*., 1993). Another example would be the sturgeon (*Acipenser sp.*), whose populations have been recorded to be declining in the Wadden Sea area from 1850 until 1918 (De Jonge,1993). However, in the beginning of the 20th century, people were still able to catch these fish in significant quantities, and the European sturgeon (*Acipenser sturio*) was still abundant (Brehm, 1908). However, starting from 1920 the population was only observed as rare, extremely rare of even extinct, depending on the record and location (Redeke, 1922; Wolff, 1983; Lotze, 2007). Similar to the European sturgeon, data on the houting (*Coregonus oxyrinchus*), spiny dogfish (*Squalus acanthias*) and thornback ray (*Raja clavata*) indicate that these species were formerly much more abundant (Fock *et al*., 2014; De Jonge, 1993), but declined and have to be classified as rare, extremely rare or have even vanished altogether in more recent years (De Jonge *et al*., 1993; Wolff, 1983; Lotze, 2005). The abundance change of the thornback ray was driven by extensive overexploitation in the form of fishery (De Vooijs, 1991) and that of the houting by similar overexploitation accompanied by damming and pollution (Lotze, 2005). No data on drivers of change for the spiny dogfish were found.

Historical timeline

Changes over time

The time period covered in our analysis was chosen to encompass the years with lower anthropogenic influence. Yet apparently, changes have occurred already decades to centuries ago from today, with habitat destruction, overexploitation and, more recently, pollution being held responsible for large-scale changes in the Wadden Sea flora and fauna (Wolff, 2000; Lotze *et al.*, 2005; Lotze, 2007; Holm, 2005; Reise, 2013).

The timeline created by Lotze et al. (2005) and shown in Table 4 goes further back in time than the scope of this project, but shows how the interplay of cultural and socio-economic factors impacted on the natural landscape, water quality and biota of the Wadden Sea. A more detailed look at the changes taking place in the Wadden Sea for the time period studied in this report has been made by Reise (2013), with additions from Holm (2005) and van Vliet (2022) and is shown in Table 5.

Even though the north of the Netherlands, as well as the islands had harbours suitable for Wadden Sea fisheries, this was not an important activity in the region in the 16th and 17th century, although there was an active small-scale fishery for local markets in the 17th century (van Vliet, 2022). During the 18th century there was a herring fishery which lasted until the early 19th century, whilst the fishery in the Zuiderzee grew from 1850 due to foreign trade, especially eel (van Vliet, 2022).

A reconstruction of the changes in fishing practice in Germany was not possible within SHIRE but should be considered in any future work on historical assessments of Wadden Sea fish.

In Denmark, Holm (2005) concluded that early modern (16th and 17th century) fisheries were based on ample fisheries resources of cod, herring and plaice. Indications of reduced fisheries were clear by the seventeenth century but the reasons for the decline cannot be ascertained at present. The nineteenth century saw renewed large catches of haddock, but by the end of the century large fish such as sturgeon were fished out, and by the early twentieth century haddock and rays were effectively extirpated.

Table 4 (continued). Timeline of human impacts and ecological changes by cultural period in the Wadden Sea. Adapted from Lotze (2005)

			Human impacts			
Time	Cultural Period	Economy	Exploitation	Habitat Change	Other Impacts	Ecological Changes
	Palaeolithic					
40000 -10000 BP	Ice Age					
	Mesolithic	**Hunter-gatherer**	**Subsistence**			**Gradual decrease**
8000 - 4900 BC	Sparse mesolithic occupation, Wadden Sea creation ca. 5500 BC	Hunting (game, birds, seals), fishing (fish, shellfish), gathering (eggs, feathers, plants)				Large terrestrial game (e.g., aurochs, elk, bear)
	Neolithic / Bronze Age	**Agriculture**	**Artisan**	**Adaptation**		**Gradual decrease**
4900 -800 BC	Neolithic time introduced ca. 4200-2800 BC, Bronze Age (2100-800 BC)	Cattle grazing, arable farming	Hunting (game, birds, seals), fishing (fish, shellfish), gathering (eggs, feathers, plants)	Settlement of river banks and heights, forest removal, marshland grazing		Large terrestrial game (e.g., aurochs, elk, bear)
	Roman / Early Medieval	**Trade**	**Artisan**	**Modification**		**Disappearance**
800 BC -AD 1050	Pre-Roman and Roman Iron Age (800 BC - AD 400), Early Medieval and Viking Age (AD 400-1050)	Long-distance trade, Frisian commerce, agriculture, basic technology same as previous	Hunting (game, birds, seals), fishing (fish, shellfish), gathering (eggs, feathers)	Settlement of marshes, dwelling mounds, ditches		Large terrestrial game (e.g., elk, bear), perhaps some large birds (pelican, flamingo)

Table 4 (continued).

		Human impacts				
Time	Cultural Period	Economy	Exploitation	Habitat Change	Other Impacts	Ecological Changes
	High / Late Medieval	**Market**	**Commercial**	**Transformation**	**River pollution**	**Decline**
AD 1050-1500	Society, Middle Ages	Exponential expansion of exchange sector, Hanseatic power, agricultural technique and extent increased	Commercialization of fishing (herring, oyster), bird hunting, whaling, seagrass harvest for dike building	Systematic embankment and drainage of coastal marshes and inland mires, low dikes, dams, and ditches, peat exploitation	Sewage, sedimentation,siltation	Large diadromous fish, large birds, wetlands; disappearance of grey seals, aurochs
	Early Modern	**Modern**	**Intensification**	**Separation**	**River pollution**	**Decline**
AD 1500-1800	Modernization	Integration into modern world economy, agriculture and maritime trade greatly intensified, islanders involved in shipping, trading, whaling	Intensified fishing, whaling, hunting of birds, seals, porpoise, collection of eggs, feathers, regulations imposed on declining resources	Separation and homogenization of landscape, modern dikes, many forelands embanked, river damming, harbour building	Sewage, sedimentation,siltation	Large groundfish, birds, wetlands; disappearance of large whales
	Late Modern	**Industrial**	**Peak and decline**	**Construction**	**Estuarine pollution**	**Decline & Loss**
AD 1800-1900	Industrialisation, Urbanisation	High days of large-scale modern agriculture and coastal shipping, industries grew	Traditional fisheries peaked and declined, new fisheries developed, bird exploitation peaked, whaling ceased	Large embankments, canalization of estuaries, river damming, transportation routes	Sewage, sedimentation, siltation	Most birds, diadromous fish, large groundfish, oysters, wetlands

Table 4 (continued).

				Human impacts		
Time	Cultural Period	Economy	Exploitation	Habitat Change	Other Impacts	Ecological Changes
	Early global	**Global**	**Industrial**	**Destruction**	**Coastal pollution**	**Loss**
AD 1900-1970	Mechanisation, warfare	Large-scale mechanisation of agriculture and fishing	Industrial-scale fisheries, trawling	Agricultural landscape stripped to essentials, large loss of brackish waters (Zuiderzee), seafloor trawling, shoreline petrification	Sewage, waste water, artificial fertilizer, pesticides, DDT, heavy metals, sedimentation, siltation	Loss of large predators (many birds, mammals, fish at low levels), habitat-building species, wetlands
	Late Global	**Tourism**	**Collapse and conservation**	**Protection**	**Multiple impacts**	**Invasion and recovery**
AD 1970-2000	Globalisation	Increased activities, boat traffic, infrastructure	Artisan inshore fishery, shellfish cultures, industrial offshore fishery collapse, species protection	Coastal defence, habitat protection, restoration efforts, National parks	Artificial fertilizer, heavy metals, pesticides, PCBs, TBT, climate change, exotic invasions	Impacts of invaders, harmful algal blooms, algal masses, diseases; recovery of some birds and seals

Table 5. Timeline of socio-morphological and fisheries developments in the Wadden Sea.

Year	Socio-morphological	Fisheries
1500	Peak size of the Wadden Sea due to flood incursions into diked, low-lying land, followed by intensive land reclamation; sand gaper *Mya arenaria* became dominant shellfish in estuarine parts of the Wadden Sea	In the mid-16th century Danish fisheries were mainly concentrated on plaice and haddock, but other species such as cod (*Gadus morhua*) and rays (Raiidae) were also targeted (Holm, 2005). During the winter months fishermen from the Dutch Wadden Sea islands fished the gullies for cod between the islands. This led to a successful trade from the islands which was led to a regulation in 1587 to limit the trade to the islanders and put on a price limit (van Vliet, 2022)
1650		Commercial fishing on flat oysters commenced. Depressed state of catches in Denmark; Danish fishing fleet dropped from 150 vessels in 1582 to 115 vessels in 1625 and 80 in 1642. The Dutch Friesian eel boats ('palingaken') had their own, free, mooring in the Thames in London for the trade in Zuiderzee eel (van Vliet, 2022). Along the north coast of Friesland in the Netherlands there was a fyke fishery for herring (van Vliet, 2022)
1750	Land claim by ditching salt marshes and building brushwood fences on tidal flats had displaced most natural shore habitats at the mainland	The 17th and 18th century fishing effort in Denmark was at a very low level compared to the nineteenth century (Holm, 2005) The main fishery throughout the area seems to have been for plaice and dab with semi-permanent wicker traps ('hammer') (Holm, 2005)
1800	Population density had doubled since 1500; coastal birds under increasing pressure of hunting and egg collection; almost 200 duck decoys in operation	Beam trawl introduced to the Danish Wadden Sea
1850	Armouring shorelines with hard materials; deepening of estuaries for large vessels begins; mining of mussel and shell beds for mortar production; systematic planting on dunes; arable farming eliminated almost all wetland polders	In Denmark in the mid-nineteenth century, a considerable fishery for haddock (*Melanogrammus aeglefinus*) developed. This lasted until the late 1890s, when the haddock fishery was reduced to a few boats (Holm, 2005). Dutch Zuiderzee fishing fleet, fishing on herring, anchovies and eel, grew due to trade with the UK and other countries (van Vliet, 2022)
1880		Commercial mussel fishing commenced in Dutch Wadden Sea
1900	Hunting tours for harbour seals; protection of coastal birds was prompted by dramatic decline during previous century	Shrimp fishing with efficient motor cutters began. Fishermen from Moddergat in the Netherlands moved to Emden to fish for cod as the new fishing vessels were too large for the local harbour (pers. Comm.). In Denmark between the 1890s and 1950, small beam-trawling dinghies fished regularly for undersized plaice and dab (*Limanda limanda*) in the Grådyb during winter months (Holm, 2005). By 1900, the number of dinghies had risen to 150 and conservation concerns caused the authorities to ban the fishery by 11th December of the same year. Through the 1930s the dinghy fishery with beam trawls was considered an important source of income to the unemployed, using an estimated number of 50 boats of between 1 and 3 metric tonnes (Holm, 2005).

Table 5 (continued).

Year	Socio-morphological	Fisheries
1925	Large-scale offensive diking of tidal flats began; extirpation of sturgeon, salmon and oyster beds; introduced grass *Spartina anglica* invaded pioneer zone of salt marshes	In Denmark salmon and eel fisheries with traps were of considerable importance through the first half of the twentieth century (Holm, 2005).
1930	Diking and damming of Vidå system; this system was previously so rich in eels, salmon, sea trout and houting that fishermen only fished in the Wadden Sea for plaice (Holm, 2005)	
1932	Damming of brackish Zuiderzee, where local herring populations vanished; wasting disease wiped out eelgrass beds in shallow waters; except for the estuaries, almost all brackish water bodies eliminated at mainland coast	Zuiderzee fisheries stopped; freshwater fisheries developed over time
1950	Native oyster went extinct; peat resources on mainland depleted	Fishing of shrimp, whelk and mussels proliferated; mussel bottom culture commenced In Denmark dab fisheries came to an end due to pollution from the fishmeal factories (Holm, 2005)
1965	Pesticide incidence at the Rhine killed coastal birds in Dutch Wadden Sea; hunting on seal and several bird species ceased	
1969	Damming of brackish Lauwerszee	Lauwerszee fisheries stopped; freshwater fisheries developed over time
1970	Massive enforcement of coastal defence; storm surge barriers and embankments strongly modified estuaries; thornback ray extirpated	Cockle fishing proliferated; catching small shrimps for animal fodder terminated

Not only have there been changes in the morphology and use of marine resources, but the sea water temperature in the Wadden Sea has shown changes in the past centuries. Showing a decrease from 1860 over 30 years until around 1890 after which it fluctuated upwards and appears to be rising more sharply since 1970 (Oost *et al.*, 2017, see Figure 8).

The occurrence of fish species in the Wadden Sea has not yet been analysed in the light of drivers such as temperature and this should be addressed in the future. This might help explain if the declining temperatures at the end of the nineteenth century were part of the reason for the observed decrease in herring in the Danish fishery, for example (Holm, 2005).

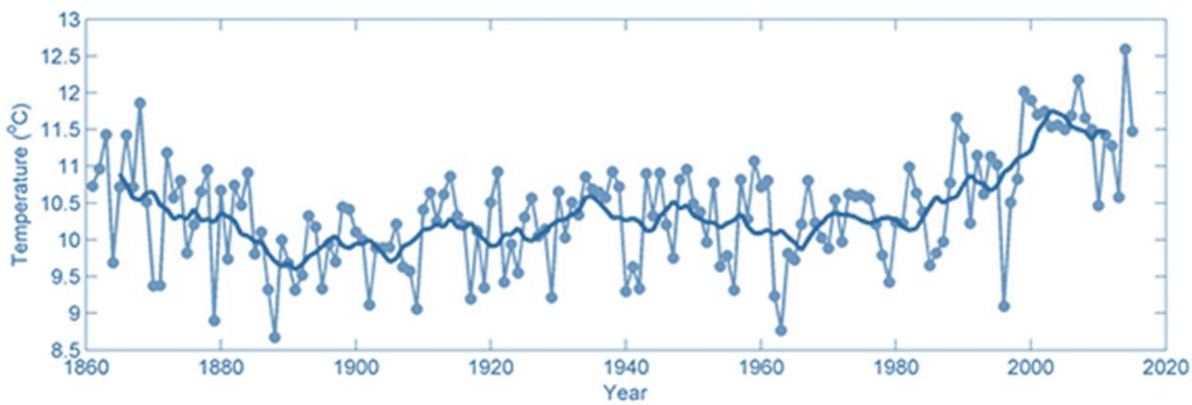

Figure 8. Average annual seawater temperature in the Marsdiep for the period 1860-2015, with a nine-year running average, showing an increase in temperature of 1.5 °C in the last 25 years. From Quality Status Report (QSR) Climate Change thematic report (Oost et al., 2017).

Using historical data

Although many archival data sources have been included in a digital system, the data sources used to obtain information change over time. This study has concentrated especially on data available both in digital forms and in books and logbooks found in musea and libraries. However, there are many different sources of data available through time. Taking 1500 as our starting date, we can reference written records and charts as well as information from expeditions, progressing to documents on exploitation and trade, newspaper articles, cookery books, photographs and interviews (McClenachan *et al.*, 2015). These could be explored further.

Incorporating historical data, however, comes at the cost of having to rely heavily on fisheries dependent information, chiefly landings data. Difficulties may arise from drawing inferences about population change from changes in fisheries landings, and from the asymmetry between information of commercial and non-commercial fish species (Box A).

Box A: Fish population dynamics represented by landings records?

The silver bullet of managing human impacts on species and ecosystems is the combination of standardized monitoring programmes -to detect and quantify change at species, community and, synoptically, at ecosystem level- and research – to understand mechanisms and processes needed to understand monitoring data. This holds for fisheries management (Heessen *et al*., 2015) as well as for protected areas such as the Wadden Sea (Tulp *et al*., 2022). As a third dimension, fisheries landings data may yield additional information, or they may even be the sole source of information on fish in a particular area in the absence of monitoring and targeted research. Commercial exploitation of fish has been a strong incentive to gather information about landings and other fisheries-related information ever since. A commercially exploited fish species has to be both marketable and abundant to support a profitable fishery. However, landings data should be used with caution and must not be confused to reflect population dynamics in a linear or strictly proportional fashion. The following example on haddock *Melanogrammus aeglefinus* fishery around the island of Heligoland illustrates this: The haddock fishery was very important in the North Sea in the 18th century, before yields dropped drastically during the 19th century. By the beginning of the 20th century, there was no longer a fishery for haddock. After the "gadoid outburst" in the 1960s and 1970s, haddock stocks declined again due to heavy fishing (Hislop, 1996; Hislop *et al*., 2015). Steam fishing was suspected to be responsible for the decline in catch yields in the 19th century, but this began before the expansion of steam fishing. Schnakenbeck (1953) describes a reorientation of fishermen to more lucrative (Arctic whaling) or simpler (tourism) occupations than haddock fishing as the reason. Around the same time, English fishing steamers (so-called "smacks") caught haddock before arriving in the nearshore fishing grounds, further reducing catches around Heligoland and the Wadden Sea islands. The relative effects of the two trends on haddock yields cannot be separated, but this example shows that fishery yields are sometimes an unreliable indicator of population size of the target species and a clear distinction must always be made between fish population and fishing fleet dynamics.

Prominent fisheries scientists, on the other hand, vigorously challenge the notion that landings data are not useful for determining the health of fish populations (e. g. Pauly, 2019). Fish abundance is only one out of many factors affecting catch size, with technological developments in gear and ship design, and change in legislation or management potentially playing an equally relevant part. However, when landings data are the only source of information on fish in a particular area, using these data and as much accompanying information as possible to draw inferences about the current state and recent and not so recent developments of the focal fish populations should always preferred over not having any information at all. There is no such thing as the perfect data source, and it is always the combination of multiple sources of information yielding the bigger picture. In this context, historical or anecdotal data can prove highly valuable even though they are not quantitative, cover only a small geographical area or a short period of time, or have not been collected in a standardized fashion (see Roberts, 2007). Mining these highly diverse data and making them available for joint analyses with contemporary information is thus highly rewarding in terms of holistic and integrated ecosystem management.

Discussion and Synthesis

Systematic Review

Total collected data

The present systematic review succeeded in identifying a host of potential sources along with records that include data on species occurring in parts of the Wadden Sea area between 1500 and 1970. Although sensitive to mistakes within records, the methods of extraction proved effective in establishing the historical occurrence of 148 species of fish and the observed abundances for many of those species. Evaluation of the collected data showcased that the dataset before 1825 was heavily dependent on fishery data, and species with commercial interest were most frequently reported. However, the amount of ecological data eventually became more abundant through the onset of survey programs at the start of the 20th century (Figure 4). This explains the gap in the data for many species which presence was most likely not worth mentioning but also helps to understand why data on fish assemblages in the Wadden Sea is scarce in general. Besides the poor documentation of fish assemblages due to only reporting species with some commercial interest, the amount of fishery data from the Wadden Sea was also likely to be limited in more recent centuries due to advances in technology which allowed fishers to fish in more profitable fishing grounds in the distant North (Holm, 2005).

Contents of the database

Most of the total dataset (86%) was comprised of the five functional groups. Although none of these groups was overrepresented, the majority of the dataset consisted of data from the pelagic and demersal marine juvenile group (22 and 21% respectively), closely followed by diadromous species (17%). These larger percentages compared to the other functional groups likely reflected the bias caused by the one-sided documentation of commercially interesting species in fishery records, which was reinforced by 79% of the data before 1825 belonging to these functional groups. Simultaneously this could explain the difference in resolution of the data collected on the flagship species (EG-Swimway, 2021), where species such as the Atlantic herring, European plaice and the European smelt were more important food sources throughout most of the study period (Holm, 2005). According to the database, data on the Atlantic herring covered the entire study period. The species was observed to be (very) abundant in a multitude of records until 1937. In the period after 1937 catch amounts were still reported to be high although herring stocks in the Dutch Wadden Sea were already being reported to be decreasing in the period of 1930–1939 likely due to seagrass disappearance. Like the Atlantic herring, data on the European plaice also covered the entire study period which also included many catch statistics. However, the number of records reporting on their abundance before 1825 was limited to a single record from the former Zuiderzee (Herklots, 1853). Similar to these species the occurrence of the European smelt could also be traced back until 1500 AD, however, with a substantial gap in the data between 1611 and 1862 AD with the exception of a few single years. Data shows that the species was recorded to be abundant in multiple years in the former Zuiderzee. After the closure of the Zuiderzee in 1932 data the species was never reported as being abundant stocks were also reported to be decreasing due to coastal construction in 1946-1969. Although restricted to parts of the study period the multitude of records on their observed abundance and catches was able to provide substantial information on the occurrence of the European smelt, unlike data on the European eelpout. The representative of the Wadden sea residents could only be traced back until 1765 in the Wadden Sea, catch statistics were scarce and data on their abundance was limited to two single years. These years, 1941 and 1969 in which the species was observed to be abundant, coincide with a period of exponential growth of ecological data in the dataset. It is therefore arguably not surprising that for a non-commercially interesting species such as the European eelpout the dataset provides more resolution in the most recent study period. Data on the tope shark also proved to be limited, however it was the only member of the marine adventitious group that was not observed to be extremely rare or absent in the Wadden Sea area in the most recent period. Limited data on this species before 1900 could likely be explained through the absence of commercial interest since the fishery on sharks only developed in the late 19th, early 20th century (Lotze, 2007) along with the possibility of incorrect naming or the inability of former observers to identify the species. Using the present dataset, it could be debated whether the tope shark was the best choice of species to be used as flagship species. The current dataset provides significantly more information on other members of the marine adventitious group such as the thornback ray, which could be used to provide information on former occurrence, abundances along with causes of decreasing stocks. The thornback ray would therefore, based on the amount of available historical data be the better pick for a flagship species.

Implications of the database

The identification of drivers responsible for changes in assemblages were deemed important for the determination of conservation strategies (Wolff, 2000). The present study only managed to identify a very limited number of such drivers. This limited number was a result of records often not mentioning any driver or relation, or being reserved in their statements on causality, but also of the methodology applied in the extraction. Since the extraction scheme only allowed for species-specific data to be extracted, data regarding drivers could not be extracted when related to fish or fauna in general. Sorting the data in the extraction scheme by functional group instead of by species name, thus switching from a species-specific to a group specific extraction of data could counter this problem by allowing more data on drivers to be added. However, by doing so this could have led to generalization of the effect of drivers on all the species within a functional group and as a result sacrificing part of the species-specific integrity of the dataset. The extraction criteria did not only limit the extraction of relevant information related to drivers. Records, before 1900, often did not specify the exact location of an observation, but instead refer to the general location, such as 'Dutch coast' or 'large rivers'. While it could almost be assumed that the authors also included the coast of the Wadden Sea in this area, it was not specified and therefore not extracted. For the same reason data was not extracted when a record mentioned the occurrence of a species but without any specification on the time of that observation.

In contrast to data on drivers, data on the abundance of species was more frequently encountered. However, these abundances mentioned in records were typically of observational nature. Unlike absolute and relative abundances, observational abundances are less comparable between different periods and prone to the shifting baselines syndrome (Pauly, 1995). A species could be observed as being abundant in year 0 but also by the next generation in year 1, even though in year 1 the species could potentially be less abundant than in year 0. Added that the observational abundance of any species is a subjective estimation and could vary between different authors/records, all data of this nature has limited quantitative implications and should be interpreted accordingly.

Limitations such as these are the result of the extensive use of grey literature. Similar historic reviews that relied on only primary literature (e.g. Lotze, 2007) or were selective in the collection of records from grey literature (e.g. Holm 2005; Wolff, 2000; Breine *et al.*, 2011) were able to draw trends regarding historical fishery landings, abundances and conclusions on what drivers were responsible for the changes in fish populations. Unlike the latter data collections or other historic reviews that made use of grey literature (Bennema & Rijnsdorp, 2015), the present dataset did not offer the possibility of inferring similar trends or conclusions based on the contents of the current dataset. However, the current dataset did provide the possibility to evaluate the accuracy of trends and conclusions drawn by previous studies. For instance, the study by Lotze (2007) revealed shifts in the importance of different fisheries where easy, accessible resources were depleted first followed by the depletion of less valuable and accessible resources. The same shifts are evident in the database where data of fisheries for finfish including diadromous species were abundant before 1900 and fisheries for flatfish and several members of the marine adventitious species became significant in the late 19th century.

Due to differences in origin or methods used for acquirement, data in the present dataset provided by different records was highly variable which caused quantifiable information to be incomparable over time. By identifying a large number of potential sources along with screening of a host of records derived from these sources for relevant content. The present study has succeeded in centralizing much of the available historic information of any species of fish in the Wadden Sea in a single database. While the database in the current state should not be used to determine conservation strategies or set targets related to historic abundances based on the limited data on drivers and former abundances. It could instead be used as an informative framework, providing a starting point for any conservation effort regarding fish assemblages in the Wadden Sea and as a means to evaluate whether conservation targets are achievable and what species to focus on, such as the case of the tope shark.

Recent developments in an historical perspective

Recent trend analyses of fish species that inhabit the Wadden Sea and that are well represented by the standardized monitoring programmes have revealed much variety in the developments during the last decades, with clear patterns being the exception (Tulp *et al.*, 2022). This goes also for the flagship species used for our preliminary analyses (see Chapter 1).

Herring varied spatially to the degree that there were even contrasting trends: Fyke catches off Texel increased significantly from the 1980s until 1990 and stabilized thereafter until they declined after 2005, whereas in another fyke survey (the so-called WMR fyke; see Tulp *et al.*, 2022 for reference), abundance increased from 2000 to 2010 followed by a decrease. In the Jade-Weser and Ems-Dollard region, the abundance trend (derived from stow net catches) increased over the last decade, and from the Elbe estuary trends were stable or uncertain (Tulp *et al.*, 2022). The unknown contributions of the effects of time, location and gear used in the monitoring programmes to the observed abundance patterns complicates interpretation even of standardized, quantitative monitoring data. But in agreement with the historical data derived from the systematic literature review, herring has always been omnipresent and abundant, with local differences. Declines of this species in the 1930ies were related to declines in eelgrass, which herring use as spawning substrate (Polte *et al.*, 2005). But although herring spawn regularly in the Wadden Sea in spring, the vast majority of herring occurring in the Wadden Sea originates from spawning events in fall and winter along the British east coast and the English Channel (e. g. Corten, 2002; Dickey-Collas *et al.*, 2010, 2015), where eelgrass is only rarely or not at all used as spawning substrate (Dickey-Collas *et al.*, 2015). In the Wadden Sea, 0-group herring (with no winter rings in the otoliths) occur in late winter/early spring as late larvae or not yet fully pigmented juveniles (Dänhardt *et al.*, 2017). Post-juveniles of age groups 1 and 2 have been observed to aggregate in huge numbers around the river plumes (Duncker & Ladiges, 1960). These patterns have been both described in historical (Duncker & Ladiges, 1960) and recent publications (Dickey-Collas *et al.*, 2015 and citations therein), indicating a spatio-temporal pattern that persists over decades, if not centuries.

Plaice is one of the most abundant and typical species of the demersal component of the Wadden Sea fish assemblage. This has been the case in the period of 1500-1970. But -with the exception of the Elbe estuary, where plaice increased until 1990 and a stabilised thereafter-plaice has declined in most areas and surveys since the 1980s, with stable periods and periods of decline alternating and varying between areas. The most conspicuous change in this species in the Wadden Sea is the disappearance of adult stages from the area. Duncker & Ladiges (1960) describe specimen of up to 24 cm as common, and Hagmeier & Kändler (1927) found juveniles smaller than 8 cm in no considerable numbers in the Wadden Sea. Nowadays it is the postlarvae settling in the Wadden Sea at around 2 cm length and growing there before they leave the area to recruit to the adult stock (Kuipers, 1977; Bergmann et al.; 1988, Goldsmith; et al. 2015). Despite a recent decline in nursery function (van der Veer *et al.*, 2011, 2022), the Wadden Sea is still considered a valuable nursery for this species.

In the inner, more estuarine areas, the marine form of smelt is one of the most abundant species in the Wadden Sea (Dänhardt, 2015). Due to its migration behaviour (Lillelund, 1961), trend interpretation on the basis of quantitative monitoring data and historical records is equally challenging. However, one clear and worrisome pattern emerges: except for a remarkable gap between 1611 and 1765, smelt was present and abundant throughout the period of investigation, and was never reported as rare. In all of the rivers flowing into the Wadden Sea, smelt has supported large fisheries for decades and became one of the most celebrated regional fisheries products. Due to an increase in coastal construction, catches were reportedly declining already between 1946 and 1969. Recent trends are almost exclusively negative or have stabilized on a very low level. The only increase in smelt abundance has been observed in the Ems-Dollard region, which was attributed to juveniles that must have originated from other river systems, since conditions spawning in the Ems do not allow successful reproduction anymore (Tulp *et al.*, 2022). Based on various historical accounts, Duncker & Ladiges (1960) describe smelt as common along the Wadden Sea coast, including the islands, whereas Dänhardt (2015) a tenfold difference in abundance between the islands and further inshore.

Eelpout could only be dated back as far as 1764 in the Wadden sea area with limited data on observed abundance and catch statistics. The species was apparently abundant in the Dutch Wadden Sea in the middle of the 20th century, but given its strong affinity with untrawlable and not easily accessible habitats, it is difficult to catch this species, let alone to derive quantitative information from the records that have to be considered coincidental.

Nonetheless, eelpout has been described as numerous and omnipresent in the Wadden Sea both several decades ago (Duncker & Ladiges, 1960) and today (Tulp *et al.*, 2022), indicating that the Wadden Sea has kept its functions for this species for a long time.

Although the tope shark is regarded as a flagship species, representing the adventitious group, the amount of collected data on this shark is limited (7 data entries) compared to other species from the same functional group (e.g., thornback ray, 19 rows; spiny dogfish, 8). Their presence can only be dated back as far as 1853 in the Dutch Wadden sea, whereas the spiny dogfish was already observed in 1764 (Annex I.). Regardless it was the only species of shark that was not observed as being extremely rare in the most recent period. Although the tope shark is not caught in the regular monitoring programmes, collaboration with professional fishermen and sea anglers has provided knowledge on the occurrence of adults and juveniles in the Wadden Sea area and the hypothesis that the area is a nursery area for the species is currently being researched. At the beginning of the 20th century, tope shark was apparently quite common in the Wadden Sea, but given the versatility of this species with large distribution ranges and high swimming speed its occurrence cannot be attributed to the Wadden Sea, but it was rather interpreted by "Professor Eherenbaum", that an individual of 12 kg being landed in Büsum in on September 24th 1926 has most likely been caught around Helgoland, where it is commonly co-occurring with plaice and haddock (Duncker & Ladiges, 1960).

How history can inform the future

Whilst it is clear that there have been many changes in the Wadden Sea in the past centuries, some of the fish species occurring in the Wadden Sea today, have been recorded since the 16th and 17th centuries as can be seen in Annex I. Species such as herring, cod, eel, flounder and plaice have continually been recorded, both in fishery sources and in ecological data. Other species, which may have been recorded as abundant in the past such as sturgeon, houting, thornback ray and spiny dogfish, are now considered extirpated. Reasons given are damming and pollution for the houting, in combination with overexploitation (Lotze, 2005) and fisheries for the thornback ray (de Vooijs, 1991). There are also some very specific examples such as the broadnosed pipefish went from being observed as abundant in 1920-22, to being rare in 1935-1941 and absent in 1935-1970 likely due to the loss of habitat in the form of closure of the Zuiderzee and the loss of eelgrass in the Wadden Sea (Redeke, 1922, 1941; De Jonge *et al.*, 1993).

The majority of historical records had a commercial background, either as anecdotal or semi-quantitative catch reports, or as accounts of cultural and societal conditions and developments centering around fish. In order to be commercially attractive and to become a fishery resource, a species has to be abundant and marketable. Thus, it can be considered an indication of abundance of a species that there was a fishery targeting it. One of the clearest examples of a once commercial species that has been exploited to extinction is the European sturgeon (Gessner et al. 1999), with current attempts to reintroduce to the river Elbe (Kirschbaum et al. 2011). Even though there is no fishery nowadays, this species is far from becoming an element of the native fish fauna in the rivers and the adjacent coastal marine areas again, despite considerable effort for its reintroduction (Gessner & Jarić 2014).

The most important lesson that can be learned from historical accounts for contemporary and future conservation of species and ecosystems is not to repeat past mistakes that are responsible for declines in species abundance (Roberts 2007). Moreover, the historical situation can highlight the conditions for successful restoration measures, rather than being used as an actual target for restoration (Kittinger *et al.*, 2015). The reconstruction of species declines and, in some sad cases, species extirpations and the role human activity played in them may also shed light on the loss of biological interactions that comes with the decline or the disappearance of a species. The loss of a species is much more a change in the species list, and to grasp its functional consequences it should always be viewed in context with its interspecific interactions. Some of these interactions even relate to humans, and when this relationship becomes economic (from an anthropocentric view), the interaction is called ecosystem service.

Historical data on fish occurrence and abundance is one component of understanding functional relationships in an ecosystem and relating human activities and, eventually, human demands to it, as illustrated e. g. in the 17 sustainable development goals (https://sdgs.un.org/goals), the majority of which relates to healthy ecosystems.

The need for a sound evidence and the historical context required to inform contemporary conservation efforts (see subchapter on shifting baselines) notwithstanding, there is an imminent need to act now, even with residual uncertainty burdening any management decisions. The literature review presented here did identify a set of impacts on fish occurrence and abundance, but at a still very generic and vague scale hampering the description (or even quantification) of cause-effect relationships. Thus, it is recommended to take a parallel approach by coming up with and rigorously testing hypotheses on pathways affecting fish populations, while at the same time forcing the precautionary approach and worst-case scenarios as ways to deal with uncertainty.

Recommendations for future work

Database

Since the present study only succeeded in extracting data from part of the identified sources there is much potential for future research to build upon the present database. As a future open-source database, the current set of data could possibly grow extensively and unlock the true potential of an informative framework on historic fish assemblages in the Wadden Sea. The biggest challenge facing unlocking this potential is arguably the collection of information on species without commercial interest before the onset of survey data around 1900. While archeological findings aid overall estimations of historical occurrence of species in the Wadden Sea, data yielded by such findings proved to be few in numbers and difficult to date. Whereas fishery records did yield substantial amounts of data, the nature of this data was typically biased around species with some sort of commercial value. For this reason, including additional fishery records derived from archives would only aid in improving the resolution of the image of historical species assemblages with commercial interest. Records derived from local museums and collections however appeared to be more promising in terms of availability of data on species with less historical value. While overlooked or deliberately unused in other historical studies (Lotze, 2007; Wolff 2000), short visits along with correspondence with these places, such as museum 't Fiskerhuske, located in Moddergat, proved to be of great value. Not only did places like these provide unique information on findings before 1900, but they also proved to be a substantial asset in the allocation of new potential sources. Subsequent studies should therefore aim to include these sources as much as possible in order to increase and versify the amount of data. Extending the study by including citizen science could also aid in collecting additional data while simultaneously improving the involvement of citizens in scientific work related to the Wadden Sea (Bonney *et al.*, 2016). However, due to the sensitivity of the database regarding inaccurate extraction of data from records, citizen involvement should be limited to the allocation of new potential records and sources, validity checks of included data and discussions with other disciplinary fields, such as historians, fishermen and governmental organizations on the implications of the dataset. The success of the inclusion of citizen science would therefore not only rely on a well-designed easily accessible platform that includes the current database along with a source list and an enquiry tool through which new sources could be suggested if they meet the requirements of the exclusion criteria (Table 2.), but also on the ability of reaching and stimulating different social strata to partake.

Besides improving the dataset in a quantitative way by extending the amount of data, future research could also involve in improving the qualitative side of the database. Such improvements could include the additional extraction of seasonal data or data on types of fishing gear but also the implementation of a system that awards records with a level of reliability in order to decrease the sensitivity of the database towards false reports or mistakes within records. It is through such improvements that this database could eventually be used to elucidate changes in abundances and their underlying drivers. This would allow the database to grow from having an informative role into attaining a more leading role in shaping future conservation strategies and targets.

Experience with the literature review

One objective of this pilot project was to provide experience and advice to guide more elaborate and in-depth literature searches in the future. The vast majority of people contacted during the literature search for SHIRE was very friendly and helpful, contributing a lot to the already good motivation of SHIRE project staff. It appeared that the most promising material on non-commercial species could be found at museums, private collections and libraries. Response via e-mail from these institutions was quite diverse, ranging from prompt replies to some archives that have not responded to this day, even after repeated inquiries. Visits or telephone calls may thus be a suitable supplement of requests via e-mail.

Archives such as the Royal Dutch archive may hold a tremendous amount of information. However, for searching those archives for something as simple as fishery records, the search methods outlined above were evidently not ideal. To ensure that all relevant material from those sources is extracted reaching out to people acquainted with searching those archives is certainly advisable.

A thorough documentation with contact details and additional information such as time and result of contact is advisable, also to avoid cross-postings which hamper the institutions‘ motivation to invest time answering the requests.

Institutions not equipped with sufficient staff to answer queries for historical fish literature may still hold valuable information, making personal visits and on site searches by project staff worthwhile. The Fishery and Maritime Museum in Esbjerg have most information about fish from the west coast of Denmark, being an example for how focussing time and resources on on-site literature searches can increase the knowledge return on effort invested.

Potential new project

This pilot study has brought together many data sources which have not been analysed until now. It is clear that a future project can explore many more data sources and may move closer to understanding the drivers that influence species, thereby throwing light on how to design management measures. The most resource and time-consuming effort for a future project will be to extract the detailed, species-specific information from the historical sources, to put them in context with contemporary conditions and to identify drivers of decline that can be influenced by changing human behaviour. An important research questions which will address the Trilateral Fish Targets will focus on how changes in habitat might influence species occurrence and abundance which could lead to a habitat – species matrix which in its turn will help identify habitat restoration measures

What is needed is a species-by species account of long-term development and an integrated analysis of how changes at the species level may have affected functional aspects at the ecosystem level, most likely mediated through trophic relationships. It might be worthwhile to focus future efforts on a limited number of species. For example, those which have been extirpated and those which have succeeded in being present for centuries; also those representative of the Trilateral Fish Targets – the flagship species.

Historical reviews focus on species (e. g. Bom et al. 2020) or species groups (e. g. Sguotti *et al.* 2016). But for being useful in conservation the information has to be scaled up at least to community level, ideally to ecosystem level by means of accounting for trophic relationships.

A central task of a future project is a clear definition how and by whom historical information is to be used for improving contemporary conservation and restoration action. In this endeavour, the competent authorities are as essential as partners as organizations representing relevant interests of nature conservation on the one hand, and of human activities potentially responsible for the impacts that put fish populations under pressure on the other hand.

Since only a small fraction of the fish species occurring in the Wadden Sea complete their entire life cycle there, another important task of a future project (or any other future activity) should be to take a life cycle perspective and link to effects and processes wherever relevant along a species' life cycle (North Sea or rivers). This is the precondition to evaluate whether there are man-made bottlenecks for fish life cycles in the Wadden Sea (where there shouldn't be any; Tulp *et al.*, 2017), or if incentives are required to improve the situation for fish outside the Wadden Sea.

During the literature search for SHIRE it became obvious that direct causes of decline were rarely found or clearly described. Knowledge about pathways by which fish become rare or even extinct is still a major bottleneck for effective conservation, but it is no option to wait until these knowledge gaps are closed. Instead, while promoting hypothesis-driven research into identifying pathways affecting fish populations, it is crucial to become explicit about how to deal with this uncertainty already now. The tool of choice is the precautionary approach. For its application, clear and coherent definitions and guidelines need to be developed to make this approach acceptable and agreeable even for stakeholders whose economic activity would be confined.

This project took a very broad time scale for analysis. A future project might identify a number of time periods in which large changes took place and study these in more detail, for those species which have been identified above.

Finally, the participation of Dutch, Danish and German colleagues with SHIRE allowed to expand the search to historical sources written in English, Dutch, Danish and German. This approach proved very effective and should thus also be used and extended in a future project.

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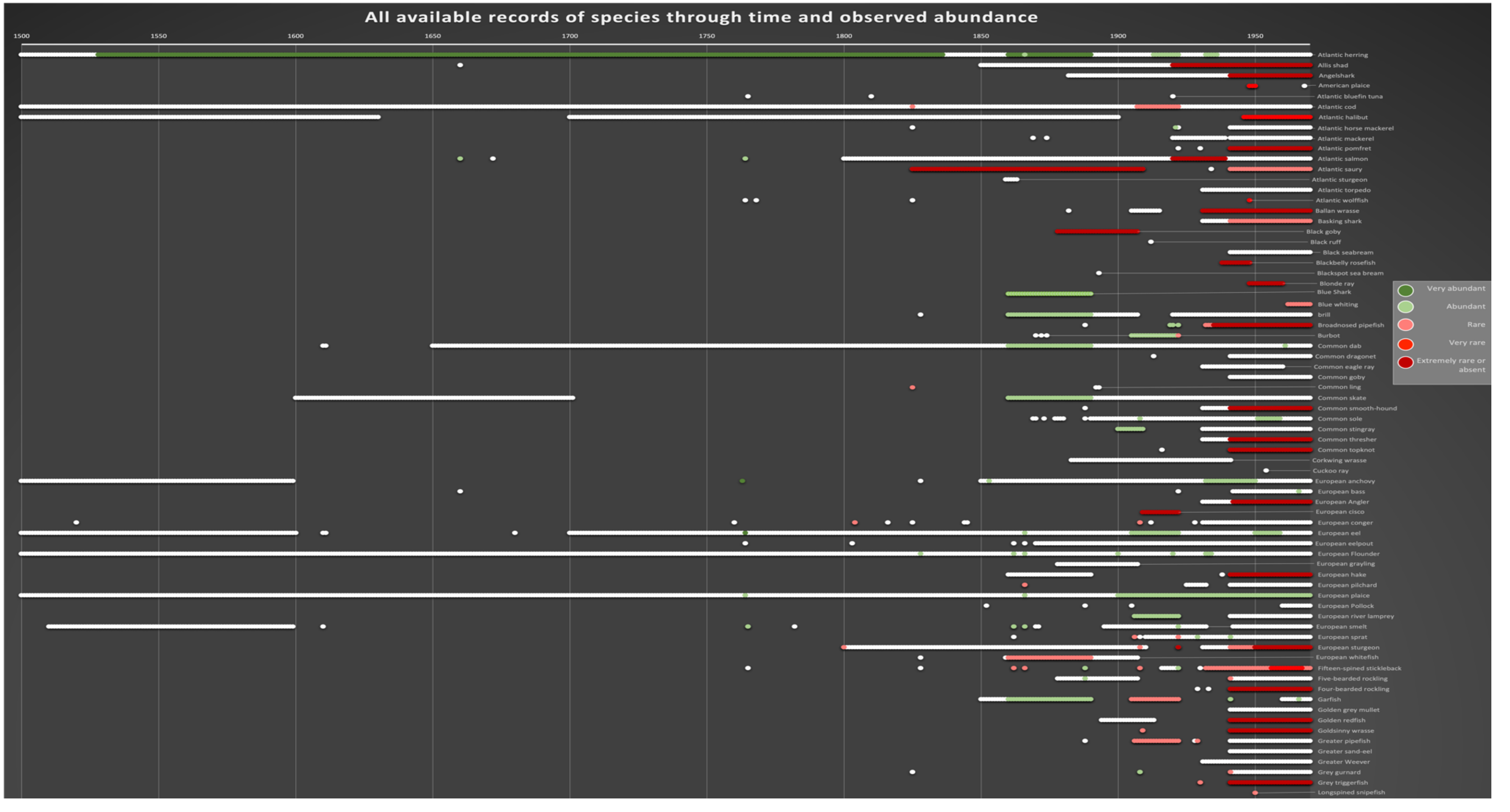
Annex I

Annex I (continued) Graphic representation of all available data on species occurrence per year between 1500 and 1970 and observed abundance (in color) as recorded in the extraction scheme.



Annex I (continued).