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Original Article

The uncertain future of the Norway lobster fisheries in the North Sea calls for new management strategies

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Nephrops (*Nephrops norvegicus*) is an economically valuable target species in the North Sea. Although individual Nephrops populations are scattered, the crustacean is managed regionally by the European Union (EU). The spatial competition for fisheries in the North Sea is growing especially due to expanding offshore wind farms (OWF) and newly implemented marine protected areas (MPA). Moreover, the Brexit affects the availability of EU fishing quotas and adds to the overall uncertainty EU fishers face. We compare landings and catches to scientifically advised quantities and perform an overlap analysis of fishing grounds with current and future OWFs and MPAs. Furthermore, we explore the German Nephrops fleet using high-resolution spatial fishing effort and catch data. Our results confirm earlier studies showing that Nephrops stocks have been fished above scientific advice. Present OWFs and MPAs marginally overlap with Nephrops fishing grounds, whereas German fishing grounds are covered up to 45% in future scenarios. Co-use strategies with OWFs could mitigate the loss of fishing opportunities. Decreased cod quotas due to Brexit and worse stock conditions, lowers Germany's capability to swap Nephrops quotas with the UK. We support the call for a new management strategy of individual Nephrops populations and the promotion of selective fishing gears.

Keywords: Brexit, demersal fishery, German fishery, marine spatial planning, offshore wind parks, resource management.

Introduction

The Norway lobster (*Nephrops norvegicus*, hereafter referred to as Nephrops) constitutes an important pillar of European fisheries generating a value of 107 M€, making it the 2nd most valuable landed shellfish species in the North Sea and Eastern Arctic region in 2018 (STECF, 2020). Since the start of commercial exploitation of Nephrops in the 1950s, the fishery grew substantially in the Celtic and North Sea, which are still the main Nephrops catch areas (Ungfors *et al.*, 2013). The main fishing nations are the United Kingdom, Denmark, Ireland, and the Netherlands (EUMOFA, 2019). Several other nations, including Germany, represent minor actors in the international Nephrops fishery. The German Nephrops fishery presents an interesting case study, as it emerged relatively recently.

In waters of the European Union (EU), Nephrops is managed through the EU Common Fisheries Policy, and is one of only two crustacean fisheries in the EU that is subject to output controls (quota or catch limits), so called total allowable catches (TAC). Nephrops TACs are set annually and based on the scientific advice provided by the International Council for the Exploration of the Sea (ICES). The EU Council Regulation allocates annual fishing quotas for each fishing area to EU member states according to the relative stability, a fixed proportional share for each country and fish stock. The relative stability is based on historical catch amounts and does not necessarily reflect present catches of EU member states. Therefore, EU member states may exchange quotas among each other (quota swaps). Although the Nephrops TAC applies on a regional scale, e.g. the entire North Sea, patchy suitable habitats for Nephrops (particular silt and clay contents) result in separate populations, which are referred to as Functional Units (FUs; Phillips, 2006; Aguzzi and Sardà, 2008).

Despite the high economic value of this fishery several issues emerge that may jeopardize its future ecological and economic viability and call for closer examination. First, the mismatch between management at a regional (i.e. North Sea) scale and much smaller scale at which discrete stocks occur has been criticized for not ensuring sustainable exploitation rates and thus risking local depletion (Williams and Carpenter, 2016; ICES, 2020a). In fact, the Nephrops stock size has been considered too low in relation to biomass reference points in one FU, and stock status is unknown for three of the nine North Sea Nephrops populations (ICES, 2020b). However, the EU management approach remains regional, although ICES releases annual scientific advices including Nephrops catch or landing recommendations for each individual FUs. Moreover, most Nephrops are caught by mixed fisheries using non-selective bottom trawls resulting in high amounts of bycatch (Briggs, 1986; Evans *et al.*, 1994; Catchpole and Revill, 2008; Cosgrove *et al.*, 2019). In fact, this diverse catch composition complicates the classification and distinction of a Nephrops fleet, since information on catch compositions, revenues, and vessel characteristics is used to group EU fisheries into so called fishing metiers (Ulrich *et al.*, 2012). Despite all these issues concerning the Nephrops fishery, peer-reviewed scientific studies with a broad geographical focus, i.e. beyond single Nephrops FUs, are scarce (Ungfors *et al.*, 2013).

The departure of the UK from the EU (Brexit) has been posing considerable uncertainty for EU Nephrops fisheries, given that the UK is allocated the largest share of the Nephrops TAC, and the main fishing grounds and FUs are located within the UK's exclusive economic zone (EEZ). In December 2020, a post-Brexit agreement was reached, which provided regulations for the joint management of over 100 shared fish stocks (European Commission, 2020a). Over a period of five and a half years (2021–2026), 25% of European fishing rights in UK territorial waters will be transferred to the UK fishing fleet. Although this does not affect the North Sea Nephrops quota allocation directly, it might influence quotas of species that are either caught in a mixed fishery with Nephrops or used to swap quotas with other EU member states. After the transition period there will be annual consultations held by the two parties on fishing opportunities with a focus on sustainable fishery management (European Commission, 2020a). Moreover, an agreement was achieved enabling quota swaps between individual EU member states and the UK (European Commission, 2021).

Like most fisheries in the North Sea, the Nephrops fishery competes for space with a large number of different stakeholder groups, such as shipping, offshore renewable energies, and nature protection (Halpern *et al.*, 2015). The growth of the offshore wind farm (OWF) sector in particular is supported by the ambitious EU strategy of reducing greenhouse gas emissions, which could lead to an extensive overlap between fishing activities and OWFs (Stelzenmüller *et al.*, 2020). Together with the future fisheries management measures of the Natura 2000 network of marine protected areas (MPAs), implemented under the Habitat and Birds Directive (Probst *et al.*, 2021), a loss of spatial fishing opportunities is likely.

Here, we describe the development of the Nephrops fishery in the North Sea since 2000 with emphasis on management, conflicts of spatial use, and implications of the Brexit. Our approach

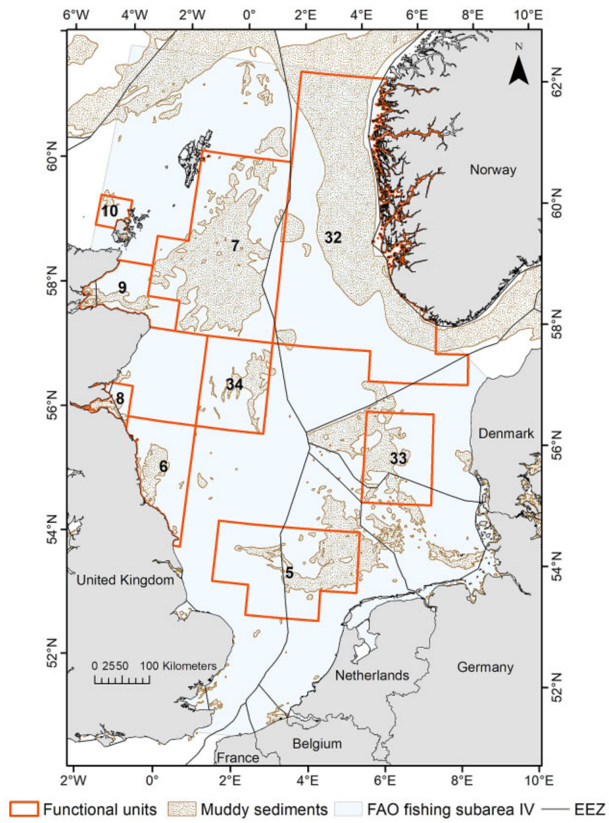

Figure 1. Map of the study area (North Sea; FAO fishing area 27 IV) featuring the nine functional units (FU) for Nephrops management, the EEZ of adjacent countries, and the distribution of suitable (muddy) sediments for Nephrops.

combines ecological, spatial, fisheries, and management information of the last two decades on Nephrops populations, i.e. FUs. We compare real and scientifically advised fishing opportunities for each Nephrops FU and perform a spatial analysis to assess the overlap of Nephrops fishing areas with current and future spatial fishing restrictions, such as OWFs and MPAs. In addition, we use logbook and spatially resolved effort data of German fisheries, as a case study for current and future challenges of the Nephrops fisheries in the German Bight. We apply a clustering approach to define German fishing practices distinguished by catch compositions.

Material and methods

International Nephrops fishing data

The study area encompasses the North Sea (FAO fishing area 27 subarea IV) and includes nine distinct Nephrops populations referred to as funcitonal units (FU; Figure 1). We obtained Nephrops landings and discards data for each FU from ICES advices for Nephrops (downloaded from www.ices.dk). In addition, ICES advice is provided for Nephrops outside of the FUs. Landing data were unavailable in ICES advices for FU34 before 2009 and the outside area before 2010. For these areas, we obtained Nephrops landings data from the Scientific, Technical and Economic Committee for Fisheries (STECF) for the North Sea from 2002 to 2018 (Gibin and Zanzi, 2020), which are compiled quarterly and by statistical rectangle (1° Longitude × 0.5° Latitude), species, and EU member state. We aggregated annual Nephrops landings by FU to complement landings from ICES advices. Furthermore, we compiled STECF landings per country and FU in the German Bight to identify fishing nations active in FUs relevant for the German fleet. STECF data only include landings from EU fleets and therefore excludes Norway, which lands considerable amounts of Nephrops in FU32. A comparison of information from ICES advices and STECF can be found in Appendix III.

If discards were available, we calculated catches by adding up landings and discards. Discard information were absent in ICES advices for the FUs 10, 33, and 34 and lacking for several years in advices of the other North Sea FUs. We gathered recommended total Nephrops catches and landings per FU from ICES advices between 2003 and 2021. Subsequently, we combined them with international Nephrops landings and catches to analyse the uptake and overshoot of advised fishing opportunities. Whenever information on discard was available, we compared catches to advised catches and in case either discards or catch advises were unavailable, we compared landings to advised landings.

Nephrops TACs are jointly set for the fishing areas 27 IV (North Sea) and EU (UK after Brexit) waters of 27 IIa (Norwegian Sea). For this area, we extracted Nephrops TAC per EU member state from annual Council Regulations of the EU (2003–2020). To assess the potential impacts of Brexit on North Sea Nephrops fisheries, we subtracted UK quotas from EU TACs and compared the results with landings (STECF) of EU member states catching Nephrops, i.e. Belgium, the Netherlands, Denmark, France, and Germany. This was done for the years 2003–2016, as complete STECF landings by country for recent years were unavailable due to confidentiality issues.

German Nephrops fishery

To identify and analyse the German Nephrops fishery, we combined two types of vessel-specific data, i.e. commercial logbooks and vessel positions based on vessel monitoring system (VMS). Logbook data are resolved by fishing trip and comprise information about weight and composition of catches, revenues, and the statistical ICES rectangle (1° longitude $\times$ 0.5° latitude) where catches were recorded. VMS data contain geographical positions of vessels, which are broadcasted roughly every 2 h (so called "pings") by German vessels. Logbook data was available from 2000 to 2019, whereas reliable VMS data were available only from 2012 to 2019. All data-processing steps were done using the R programming language (R Core Team, 2019).

Fishing logbooks

We pre-selected vessels that targeted Nephrops within the last 20 years by choosing all vessels with a track record of more than 10% annual Nephrops catches in at least 1 year in the logbook data. Moreover, we excluded vessels that primarily fished in the Baltic Sea by choosing only those vessels that spent at least 50% of their annual fishing trips in the North Sea. Subsequently, we compiled all catch information of these vessels, selected only catch records of the ten most caught species and, per fishing trip, converted total to proportional catches. Based on the resulting data set, we created a distance matrix (Euclidean distance) using the vegan package for R (Oksanen *et al.*, 2019). We performed hierarchical agglomerative clustering using the average linkage method (Legendre and Legendre, 2012) and increased the number of clusters until a cluster emerged that mainly caught Nephrops. We ended up with seven fishery clusters, which we named after their main target species (Appendix I).

We visually explored the temporal distribution of the resulting fishery clusters and identified the year 2006 to be the first with fishing trips in the cluster targeting Nephrops. To analyse the development of the emerging German Nephrops fishery, we calculated changes of relative fishing activity before and after 2006 for each fishery cluster. First, we calculated the proportional fishing activity vessels spent in fishing clusters for both time periods, meaning 2000–2005 and 2006–2019, by dividing the number of fishing trips per cluster by the total number of fishing trips of the respective vessel. We removed vessels with fishing activity in only one time period and clusters with less than 30 trips across the entire study period, which made up less than 1% of all data. Second, we calculated the difference of proportional fishing activity before and after 2006 per cluster and vessel. Third, we summed up all proportional changes in fishing activity for each pair of fishing cluster. Finally, we visualized the shifts from one fishery cluster to another as a chord diagram using the circlize package for R (Gu, 2014).

VMS

In a following step, we obtained VMS data for previously identified fishery clusters targeting Nephrops to analyse their spatial distribution. We removed duplicates and data points in ports from the VMS data and identified fishing pings, which are affiliated to slower speeds than when the vessel was steaming. We identified fishing pings by applying the *activityTacsat* function from the VMStools package for R (Hintzen *et al.*, 2012). Subsequently, we selected only pings affiliated with fishing activity. Through merging logbook with VMS data (see Appendix II for details), VMS data could be grouped according to the previously identified fishery clusters. Then, we generated their utility distribution, that is a function describing the probability of occurrence in a spatial area, using the least-square cross-validation method with the adehabitatHR package for R (Calenge, 2006). We visualized core fishing areas by extracting 90% contours, referring to the minimum area in which vessels of a respective cluster have a 90% chance of occurrence.

Quotas

We received information on request about German Nephrops quotas (2003–2019) from the German Federal Office for Agriculture and Food (BLE; www.ble.de). Annual Nephrops quotas are assigned to EU member states and may then be swapped among countries. We received information on individual quota swaps from the BLE, which enabled us to quantify the amount of Nephrops quota Germany received from other EU member states and for what quota species it was swapped for.

Spatial overlap analysis

To assess the current and future spatial competition of the Nephrops fishery with other human uses in the North Sea, we obtained a data set on offshore wind farm (OWF) development from *4C Offshore Ltd* (status March 2021) and marine Natura 2000 sites from the European Environmental Agency (status December 2020). Like all trawl fisheries, Nephrops trawler activity is prohibited in and around OWFs due to the risk of damaging OWF structures and submarine cables. We grouped OWFs in the North Sea according to three categories: (a) existing OWFs (sites that generate power or

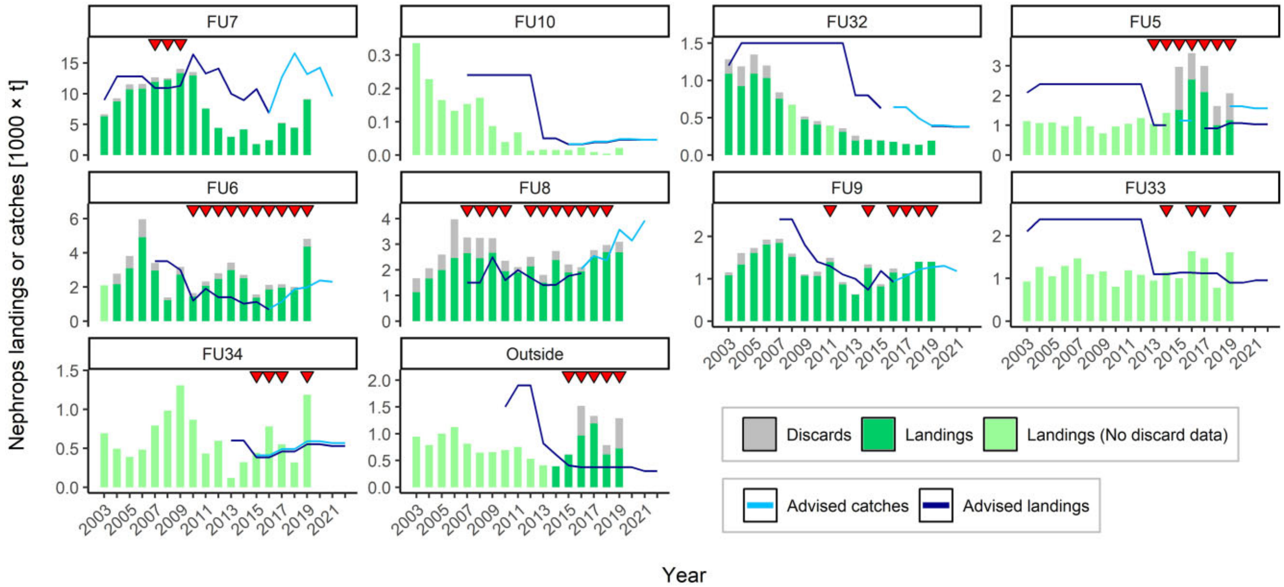

Figure 2. International Nephrops landings and catches, as well as advised total catches (light blue) or landings (dark blue) from ICES per functional units (FU). Catches are composed of landings (greens) and discards (grey). Years for which there were available discard information are coloured in dark green. The red arrows above bars indicate years with surpassed catch or landings recommendations.

were under construction in 2020), (b) planned OWFs (all other sites with a construction start date between 2020 and 2033), and (c) potential sites (all sites without a construction start date minus those projects that have been cancelled or with failed proposals).

Furthermore, given that Nephrops FUs are based on statistical rectangles (1° Longitude × 0.5° Latitude) and do not represent fine-scale fishing grounds, we determined the suitable habitat for Nephrops within FUs using muddy sediment occurrence. We obtained substrate data from Emodnet (www.emodnet.eu; status December 2020) and used the classification "mud to sandy mud" to characterize suitable Nephrops habitats. Subsequently, we determined relative spatial overlaps between present and future spatial restrictions, i.e. the three OWF groups and Natura 2000 sites, and all FUs in the North Sea, Nephrops habitats, and core fishing areas of the German fleet. All spatial analyses were done using ArcGIS 10.3.

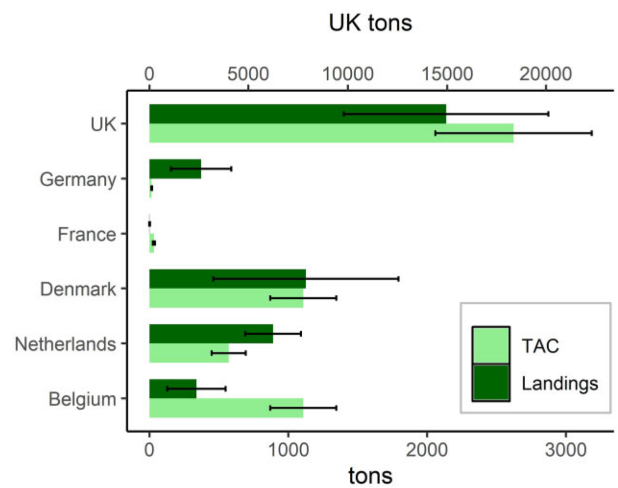

Figure 3. Yearly averages (2003–2016) of Nephrops landings and total allowable catches (TAC) in the North Sea per country. Displayed are all countries with a Nephrops TAC in the fishing area 27 IV and IIa. Error bars indicate standard deviation across years.

Results

International Nephrops landings

Total international landings of Nephrops in the North Sea generally decreased from 2003 to 2018 peaking in 2007 with 24 kt (Appendix III). Across the entire time range, landings were highest in FU7 (7.3 kt), FU8 (2.1 kt), and FU6 (2 kt), all located in the UK exclusive economic zone (EEZ).

In only two out of nine North Sea Nephrops FUs, catches or landings have not been exceeding the advised amounts in any year (Figure 2). From the years with available catches or landings and advised quantities, catches or landings exceed advised quantities in most years in the FUs 6 (77%) and 8 (85%). Landings or catches from the FUs 5, 9, 33, 34, and the outside region (North Sea area outside of FUs) exceeded advised quantities only after 2011, whereas FU 7 exceeded advised fishing opportunities only slightly from 2007 to 2009. On average, proportional excesses were highest in the outside area (216%) and lowest in FU7 (113%). For the years 2019–2021, no EU landing or catch data was available at the time we performed this analysis, but scientific advices remained on a similar level compared to previous years, except for FUs 7 and 8, with the former showing a decrease and the latter an increase.

A comparison of annual averages of landings and TACs by country (Figure 3) revealed that the Netherlands and Germany have been fishing Nephrops above their quotas and, therefore, acquired additional catch capacities from other EU member states (Appendix IV). Germany required the highest additional quota on average (356 t) followed by the Netherlands (320 t). The UK, France, and Belgium fished below their quotas and therefore had capacities to swap their Nephrops quota with other EU member states. The UK had by far the highest average quota swap capacity (3400 t) followed by Belgium (770 t) and France (31 t). Denmark's average Nephrops

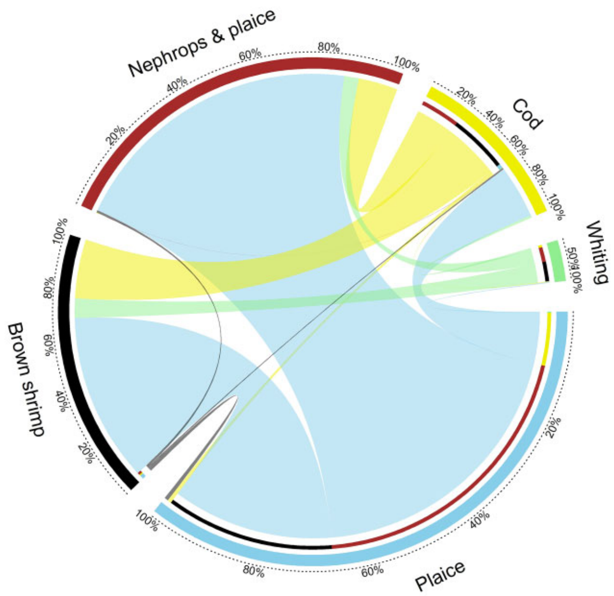

Figure 4. The chord diagram shows the relative shift of fishing hours of all German vessels that ever participated in the Nephrops fishery (2000–2019). The connections represent flows from before to after 2006 between source clusters (outer wide circle) and target clusters (inner thin circle).

landings were only slightly lower than its TAC. Due to unavailable international catch and discards data, we compared landings to national quotas. This is a conservative comparison, because landings do not include discarded Nephrops at sea.

German *Nephrops* fisheries

Emergence of the German Nephrops fleet

We identified 22 vessels that targeted Nephrops in at least 1 year between 2000 and 2019 in the North Sea. Our cluster analysis revealed a distinct variation in fishing activities across these vessels over the past 20 years. We identified seven fishery clusters, which could be characterized by their main target assemblage: (I) *plaice*, (II) *whiting*, (III) *cod*, (IV) *sole*, (V) *brown shrimp*, (VI) *Nephrops & plaice*, and (VII) *brown crab.* Most fishery clusters target spatially different areas underlining that they are distinct fishing practices (see Appendix I for details). The only clusters catching substantial amounts of Nephrops (among the ten most caught species) were *Nephrops & plaice* and *plaice,* the former primarily targeting Nephrops, whereas the latter primarily caught plaice and other demersal species with minor Nephrops amounts. The temporal composition of fishery clusters per year showed that the *Nephrops & plaice* group was merely present before 2006 and then remained stable with about 100–200 trips per year (Appendix I). The *brown shrimp* fishery cluster was another fishing practice that emerged in 2006 within the defined fleet. The other fishery clusters became less abundant over the time period and the *whiting* and *brown crab* groups disappeared in most years after 2012. Moreover, the clusters *brown crab* and *sole* were relatively small clusters with less than 30 trips (< 1% of all trips) and thus removed from the analysis.

As shown in Figure 4, German vessels that switched to *Nephrops & plaice* after 2006 were previously engaging in the following fishery clusters (percentages represent proportional fishing activity of all vessels in the *Nephrops & plaice* cluster): *plaice* (82%), *cod* (11%), *whiting* (4%), and *brown shrimp* (< 1%). Furthermore, a large amount of fishing activity became allocated to the *brown shrimp* cluster, emerging from the *plaice*, *cod*, and *whiting* clusters.

Spatial distribution, infrastructure, and quotas

The German Nephrops fleet targets FU5 and FU33 (Figure 5), both located in the German Bight and, among all FUs, closest to German harbours (Figure 1). The former is located in the EEZs of the Netherlands and UK, whereas the latter is located in the German and Danish EEZs. Several other nations are participating in the Nephrops fishery in the German Bight. Ranked in terms of landed Nephrops, from highest to lowest these are: the UK, the Netherlands, Belgium, Germany, Ireland, and France (Figure 5). Denmark predominantly fishes in FU33 and the UK in FU5, which represents the FUs closest to their coastlines. Moreover, there is a considerable amount of Nephrops landed from outside of the FUs suggesting some mismatch of FUs and catch areas. This is also supported by the large areas of suitable Nephrops habitat adjacent to the FUs 5 and 33 (Figure 1). Note that these results are based on STECF data excluding non-EU countries, such as Norway.

Based on an annual average, German vessels mainly landed Nephrops in Dutch (450 t) followed by German (31 t) and Danish ports (11 t), clearly highlighting the strong dependency of the German Nephrops fishery on international infrastructure (Appendix IV).

The UK receives by far the largest share of North Sea Nephrops quota, followed by Belgium, Denmark, the Netherlands, France, and Germany (Figure 6). The German share of the North Sea Nephrops TAC is extremely low (0.08%), which resulted in an annual average of just 17 t (2003–2020). To increase fishing opportunities, Germany swapped quota with other member states, mainly the UK, followed by Belgium and the Netherlands (Figure 6). From 2003 to 2019, Germany performed 190 swaps gaining a total of 9100 t of Nephrops quota (Appendix IV). With regard to the number of transfers, most species quotas used as exchange currency were cod (42), whiting (27), ling (24), anglerfish (21), haddock (17), hake (14), and sole (14). Despite the known received quantities of Nephrops quota, the data resolution did not allow to quantify the quotas given by Germany.

Current and future spatial constraints for the Nephrops fishery

North Sea

Currently only a minor fraction of FUs overlaps with OWFs and until 2033, on average, not even 1% of FUs will overlap with planned OWFs (Table 1; Figure 7a). However, if we consider potential OWF areas (those without starting date), we found an overlap of on average 8% per FU. An area of similar size (8%) could be closed to fishing under Natura 2000 regulations. While the majority of FUs face none or little spatial constraints from both OWF developments and Natura 2000 (0–6% when only suitable mud areas are considered), the FUs 5, 9, and 33 may face substantial losses of up to 28% of the fishing area.

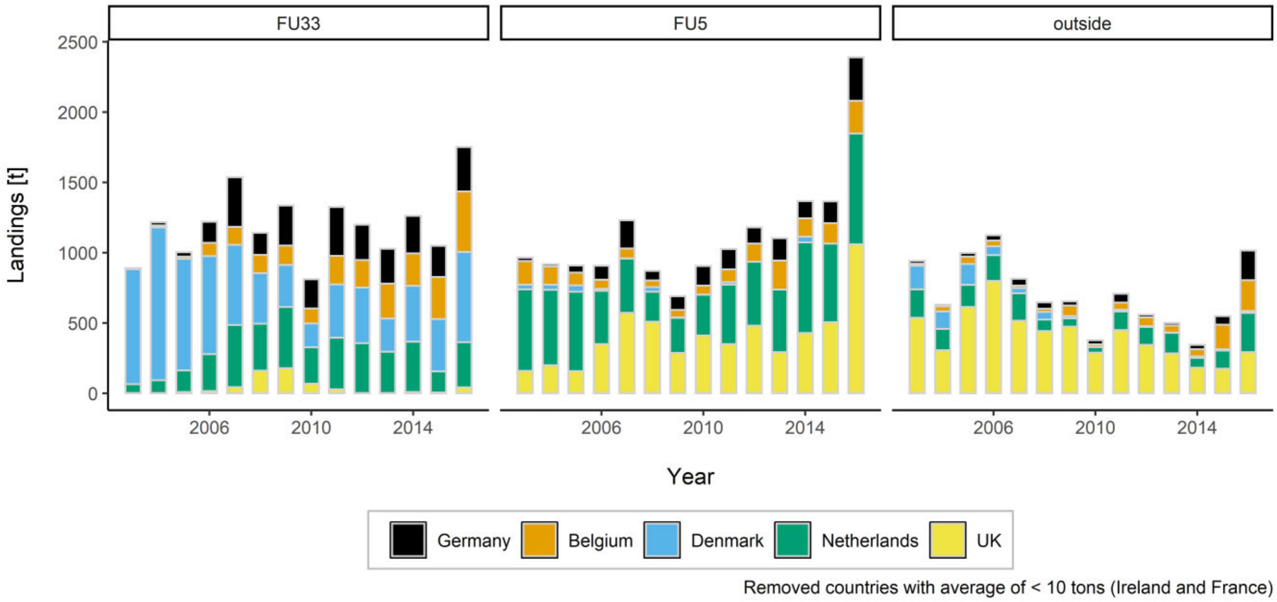

Figure 5. Annual international Nephrops landings in the German Bight split into catches inside and outside of functional units (FU) .

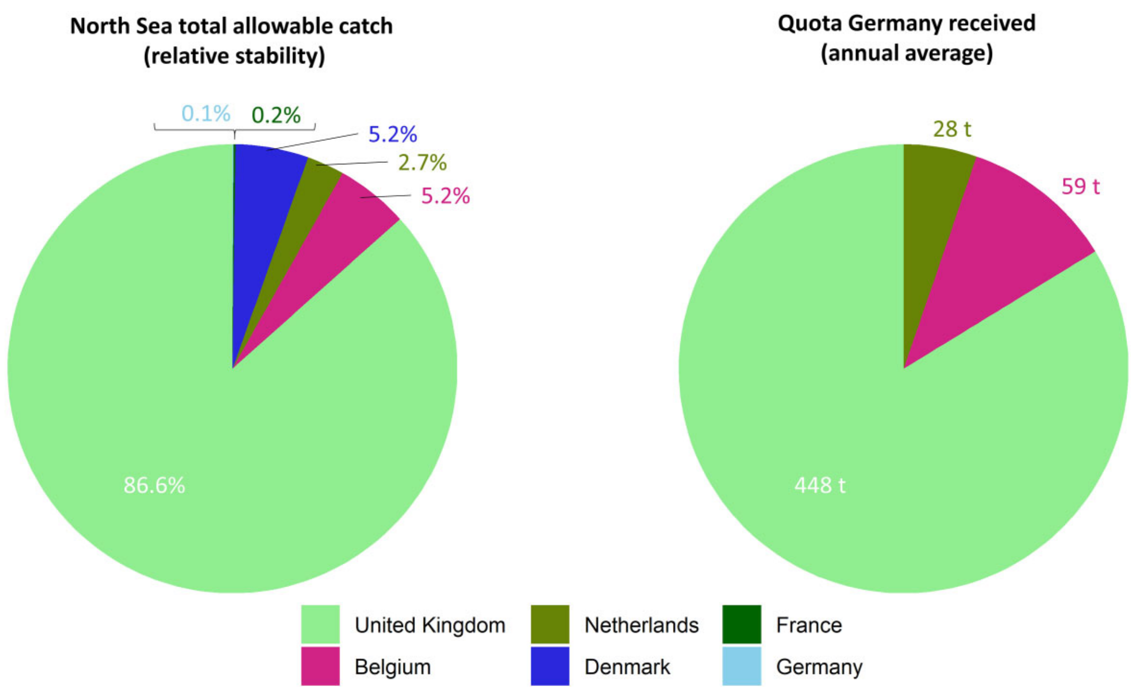

Figure 6. Nephrops total allowable catch (TAC) in the North Sea as percentage per country (pre-Brexit), which is also referred to as relative stability (left) and annual averages of Nephrops quota (2003–2019) Germany received from other countries (right).

German Nephrops fishery

There was almost no overlap (1%) of planned OWFs (until 2033) and the two German fishery clusters catching Nephrops (*plaice* and *Nephrops & plaice*; Table 1; Figure 7b). However, this is a conservative estimate including only OWFs for which a construction date was set. In fact, the overlap of both fishery clusters with potential OWF developmental areas and Natura 2000 sites was considerably larger. The relative overlap area was 45% for the *Nephrops & plaice* and 31% for the *plaice* cluster.

Table 1. Relative spatial overlap as percentage of functional unit (FU) for Nephrops management and suitable Nephrops habitat (mud) per FU with Natura 2000 sites and offshore wind frams (OWF) at three different developmental stages: existing (before 2020), planned (2020–2033), and potential (without starting date). The bottom part displays the overlap of fishing core areas of German Nephrops fishery clusters with OWF developmental stages and Natura 2000 sites.

	Mud content	OWF existing	OWF existing (mud)	OWF planned	OWF planned (mud)	OWF potential	OWF potential (mud)	N2000	N2000 (mud)	N2000 and all OWFs	N2000 and all OWFs (mud)
FU											
10	12.9	0.0	0.0	0.0	0.0	0.6	0.0	2.4	0.0	3.1	0.0
32	42.7	0.0	0.0	1.0	2.1	1.3	2.1	0.0	0.0	1.4	2.2
33	37.6	0.2	0.0	0.0	0.0	30.2	27.5	1.3	0.2	31.8	27.7
34	20.0	0.0	0.0	0.0	0.0	6.8	0.9	0.0	0.0	6.8	0.9
5	27.7	2.4	0.0	3.5	0.0	22.0	1.5	39.8	22.1	52.7	23.5
6	19.0	0.0	0.0	0.0	0.0	0.1	0.2	6.1	2.9	6.3	3.3
7	49.8	0.0	0.0	0.0	0.0	3.6	1.2	0.7	0.1	4.2	1.3
8	23.6	3.0	2.0	0.7	0.0	2.7	0.8	9.8	2.7	16.2	5.6
9	18.5	3.6	0.0	1.9	0.0	6.1	0.0	13.0	27.6	24.8	27.6
Mean	28.0	1.0	0.2	0.8	0.2	8.2	3.8	8.1	6.2	16.4	10.2
Fishing areas											
Nephrops & plaice	–	0	–	1.2	–	22.6	–	21.3	–	45.1	–
Plaice	–	0	–	0.9	–	17.5	–	13.5	–	30.7	–

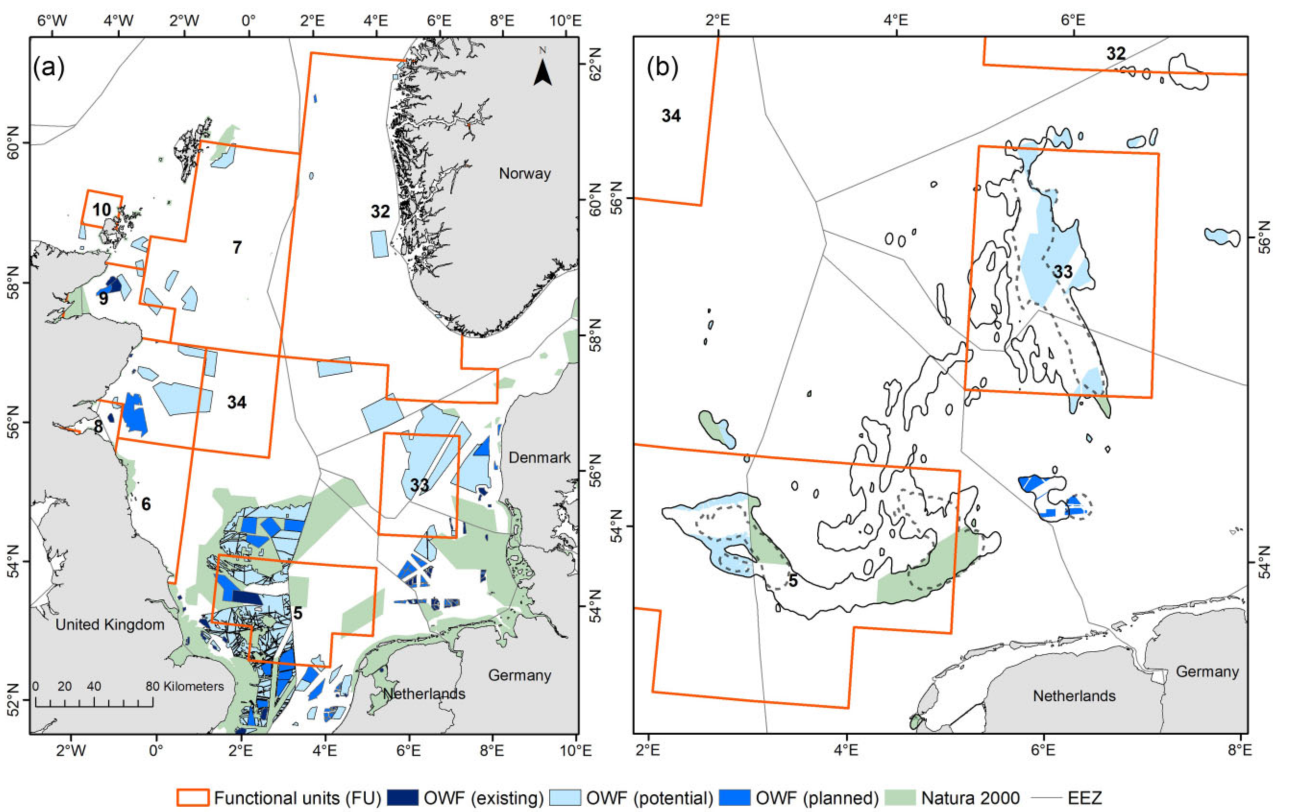

Figure 7. (a) The North Sea with Nephrops functional units (FU), designated Natura 2000 conservation sites (in green), and offshore wind farms (OWF) at different developmental stages: existing (black; before 2020), planned (dark blue; 2020–2033), and potential (light blue; without starting date); (b) The German Bight with the core fishing areas of the German fishing fishery clusters *Nephrops & plaice* (dashed line) and *plaice* (solid line) and their overlap with different stages of OWF development and Natura 2000 conservation sites.

Discussion

Our analysis revealed a heterogenous distribution of international Nephrops fishing activities in the North Sea. Some functional units (FU) were exploited above the advice, yet the overall quota was not exceeded. To date, Nephrops FUs are not affected by spatial restrictions due to other sectoral plans, i.e.offshore wind farms (OWF) or marine portected areas (MPA). However, this will change with expanding OWFs and future MPAs being implemented in the EU Natura 2000 network. In particular FUs in the German Bight and core fishing areas of the German Nephrops fleet could experience spatial constraints of up to 45% due to the expansion of OWFs and newly implemented MPAs.

The North Sea Nephrops fishery

Fisheries management and ecological considerations

Although the overall total allowable catch (TAC) for Nephrops in the North Sea has not been exceeded in the past two decades, several annual landings and catches from individual Nephrops populations (FUs) were higher than advised by ICES. Out of the nine FUs in the North Sea, Nephrops landings or catches exceeded recommended fishing opportunities in seven FUs in at least 1 year. This is problematic from a marine conservation point of view, not only because the fishery threatens the health of the stock itself, but also because Nephrops is mainly caught in a mixed fishery with high bycatches using bottom trawls (Revill *et al.*, 2006; Catchpole and Revill, 2008; Ungfors *et al.*, 2013). Therefore, the concentration of fishing effort of Nephrops trawlers on several FUs might have negative effects for the whole benthic ecosystem. Bycatch species, which are of an economic value, may pose an important additional source of income for Nephrops fishers (Bailey *et al.*, 2012). However, the proportion of undersized finfish and other non-marketable species is high and the Nephrops fishery has been identified as one of the main contributors to European unwanted bycatches (Catchpole *et al.*, 2006; Catchpole and Revill, 2008). The reduction of unwanted bycatch could be achieved by using alternative fishing gears (Catchpole and Revill, 2008; Santos, 2016; Cosgrove *et al.*, 2019). One example would be passive gears, such as creels, which have a higher selectivity and a lower impact on the sea floor (Hornborg *et al.*, 2017). The usage of more selective trawls like "Sepnet" or trawls with selection grids are further examples how unwanted bycatch may be reduced (Catchpole and Revill, 2008). The promotion of selective and sustainable gears is also stated in the EU common fisheries policy article 17: "*[…] member states shall use transparent and objective criteria including those of environmental, social and economic nature. The criteria to be used may include, inter alia, the impact of fishing on the environment, the history of compliance, the contribution to the local economy […]*" (European Union, 2013). It further states that "*[…] member states shall endeavour to provide incentives to fishing vessels deploying selective fishing gear […].*" As creels are more selective and may result in higher economic return (Leocádio *et al.*, 2012; Williams and Carpenter, 2016; Hornborg *et al.*, 2017), EU member states should create incentives to switch from Nephrops trawls to creels. However, in highly mixed Nephrops fisheries, which gain value by catching many different species, selective gears might be less economically viable.

Given that Nephrops is a rather sedentary species with specific habitat requirements (Johnson *et al.*, 2013), populations are unable to shift to other areas. A major task in conserving Nephrops populations is thus to safeguard their habitats by managing the fisheries on each FU individually, rather than the entire North Sea (Williams and Carpenter, 2016; ICES, 2020a). Individual fisheries management should be based on sufficient knowledge about stock status in each FU. As there is still insufficient scientific information to estimate stock sizes for the FUs 5, 32, and 34 (ICES, 2020c), further ecological surveys in these FUs would be necessary. Climate change may pose another stressor for Nephrops, as ocean acidification has been observed to negatively affect Nephrops' physiology (Hernroth *et al.*, 2012; Johnson *et al.*, 2013). Moreover, Nephrops is habitat-bound and thus unable to mitigate unfavourable conditions by northward shifts of populations, as it has been observed for plaice, cod, and seabass (Colman *et al.*, 2008; Engelhard *et al.*, 2011; Neat *et al.*, 2014).

Spatial competition in the North Sea

Our spatial analysis suggests that OWFs and Natura 2000 sites overlap only marginally with the North Sea Nephrops fisheries, especially if suitable Nephrops habitats rather than FUs are considered. Furthermore, the most productive FUs in terms of total landings, all located in UK waters, are among the least affected. However, there are vast differences among FUs ranging from hardly overlapping with OWFs and Natura 2000 sites to more than half of the area covered. This could indeed pose challenges, in particular for those fleets operating in FUs with large losses of fishing areas, as bottom trawling is prohibited in OWFs and largely restricted in Nature 2000 sites (Probst *et al.*, 2021; Stelzenmüller *et al.*, 2021). Displacement options for the fisheries are limited, due to strong habitat requirements of Nephrops. In addition, OWFs may function as an obstacle for fishing vessels if they do not provide navigation corridors, potentially increasing time and fuel used by fishers to drive to fishing grounds. Underwater cables connecting OWFs to the main grid may further restrict bottom trawl activity if they are not burrowed deep enough (Rességuier *et al.*, 2009). One opportunity to reduce the impact of OWFs on fisheries is the introduction of co-location options and hence enable fishers to continue catching Nephrops in OWFs using passive gears, such as creels (Leocádio *et al.*, 2012; Stelzenmüller *et al.*, 2021)

The German Nephrops fleet—a recent adaptation with an uncertain future

Our findings show that the German Nephrops fishery emerged in 2006 and originated from other fisheries targeting demersal species. The reason for this shift might be an adaptation to ecological and economic boundary conditions. Some fishers who originally targeted cod were likely forced to switch to another fishery, since cod catches have been declining in the southern and central North Sea as a result of a combination of overfishing, climate change, and falling recruitment (Cook *et al.*, 1997; Beaugrand *et al.*, 2003; Fock *et al.*, 2014). By the end of 2019, there were almost no fishers left targeting cod in the considered fleet. Another reason might be low market prices for flatfish in the years before 2006. As a consequence, the demersal fishery targeting flatfish had become less profitable, making the option of switching to a Nephrops fishery economically more attractive.

Spatial competition in the German Bight

Core areas of the German Nephrops fishery will be spatially constrained by Natura 2000 sites. Although a ban of most bottom trawling in Natura 2000 sites is likely, fishing restrictions have not yet been finalized and therefore the real impact cannot be assessed at this point. When considering all potential OWFs and Natura 2000 sites, almost half of the Nephrops core fishing area would be covered and therefore likely unavailable for bottom trawling. Although this is the extreme scenario in terms of OWF expansion, ambitious national and EU climate targets (European Commission, 2020b) support the renewable offshore energy sector in the North Sea and indicate that it is indeed realistic.

The impact of Brexit

We have shown that the German and Dutch Nephrops fleets are dependent on additional Nephrops quotas acquired from other countries and thus might be most affected by the Brexit. Although both countries will still be able to swap quotas with the UK, decreased quotas of other species may affect their swapping capabilities. Germany used mainly cod quotas in exchange for UK Nephrops quotas, however, German North Sea cod TACs have been decreasing in the last decades due to the poor status of the southern North Sea cod stock (ICES, 2019). Moreover, the EU–UK trade and cooperation agreement determines a decrease of 19% cod TAC for each EU member state from 2020 to 2025 (European Commission, 2020c; European Union, 2021), meaning that Germany might lack sufficient quota swapping currency to sustain its Nephrops fishery.

The future of the German Nephrops fishery

Currently, Nephrops represents a commercially important species in the German fisheries. Whether this fishery can be maintained or even expanded depends on several aspects. Activities of the German Nephrops fishery almost completely coincided spatially over time (Appendix IV), underpinning the strong habitat requirements of Nephrops (Johnson *et al.*, 2013; Lolas *et al.,* 2021). On the other hand, this highlights the vulnerability of the fishery, since, as it is the case for the target species itself, the fishery cannot move to alternative fishing grounds. In combination with the newly implemented OWFs and Natura 2000 sites, this will lead to substantial constraints of the German Nephrops fishery in the next few decades. The Brexit poses a more immediate threat for the German Nephrops fishery due to reduced Cod quota until 2025 and, thus, fewer swapping capacities for Nephrops quotas. However, the most general and uncertain effect will be due to climate change and affiliated changes, i.e. warming North Sea waters and ocean acidification. Moreover, past landings and catches from FUs in the German Bight surpassed ICES advices indicating unsustainable fishing and risking local depletions, that is despite ICES advices for FUs 5 and 33 recommending a decrease in catches since 2013. Therefore, from a conservation perspective, Nephrops fisheries in the German Bight should decrease in comparison to previous years, rather than expand. Overall, our results point to reduced future opportunities for the German fishers targeting Nephrops in the German Bight. Therefore, possible adaptations would be either to switch to alternative fisheries or market lower catch amounts at a higher price. Switching to more selective gears, e.g. creels, might offer the chance to advertise the landed Nephrops as being caught more sustainably, thus justifying a higher price.

Our analysis focused on the evaluation of importance of distinct spatial areas for the German Nephrops fishery, hence not providing a measure of uncertainty for various future spatial use scenarios. However, our results provide an important baseline for subsequent studies of the spatio-temporal dynamics of this fishery and the effects of spatial use restrictions, as well as climate change.

Conclusions

Our results point to an exhaustion of the North Sea Nephrops fishing capacities, supporting the call for a precautionary and well-defined management for Nephrops, including individual regulations for stocks. Further ecological and fisheries research is needed to develop accurate stock assessments and explore the consequences of climate change on North Sea Nephrops. While the current and future spatial restrictions in most Nephrops fishing grounds in the North Sea are marginal overall, those in the German Bight will face a loss of up to almost 45% due to OWF expansion and fisheries regulations related to Natura 2000 sites. Co-location of OWF and fisheries including a switch to passive and more selective fishing gears could mitigate the loss of fishing opportunities and sustain fishers' livelihoods. Although the Brexit will not influence Nephrops quota distribution in the North Sea, cutbacks of other species TACs might reduce the swapping capacities of countries to acquire Nephrops quota from the UK. In the case of Germany, decreased cod quotas, will lower the ability to obtain Nephrops quota. Furthermore, our findings indicate that German fishers switched to Nephrops because of its high economic value and the declining availability of other former target species in the German Bight. Overall, in this study we analysed the various influences on international and German Nephrops fisheries from different angles. Our study highlights the need for cumulative impact assessments to understand historic developments in fisheries and to judge on upcoming risks. Only with this knowledge target-oriented mitigation measures may be recommended.

Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

Data availability statement

The majority of the data underlying this article is accessible in public repositories or the supplementary material. Details on the German fishing data cannot be shared due to commercial sensitive information. Spatial polygons of offshore windfarms cannot be made publicly available, because a license was purchased.

Authors contribution

NS, JL, HR, and VS were responsible for the conceptualization and design, JL and NS collected the data; JL analysed the German case study data; HR performed the spatial overlap analysis; AK and JB helped to interpret the results; JL lead the writing process; and all authors revised and improved the manuscript.

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