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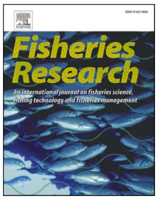

Full length article

Ecological risk assessment of invertebrates caught in Swedish west-coast fisheries

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ABSTRACT

Ecological risk assessments are important as scientific support for the implementation of ecosystem-based fisheries management. Marine invertebrates are important to ecosystem structure and function and may be sensitive to fishing pressure. Some are also of increasing commercial value – but have hitherto not been paid much attention to in ecological risk assessments. Here, catches of invertebrates in Swedish west-coast fisheries with demersal trawls and creels are examined from an ecological risk assessment perspective. It is found that few non-commercial invertebrate species have been regularly recorded in onboard observer programs. Furthermore, for being a comparatively well-studied area, it is striking to find that out of the 93 species included, 56% could be classified as data deficient in terms of known attributes needed to perform basic ecological risk assessments. This implies that there is little or no available information on the basic life history traits important for estimating productivity. Additionally, onboard observer data for invertebrates are inadequate beyond targeted commercial species for robust statistical analysis on volumes generated over time and between fisheries. However, over 18% of the studied species are categorized as red-listed on the Swedish IUCN Red List. Combined with the few records available in observer data programs, the study illustrates the need to pay more attention to marine invertebrates in fisheries monitoring programs and research, especially bycaught and non-commercial invertebrate species.

1. Introduction

With the implementation of ecosystem-based fisheries management (EBFM), there is an increased need to look beyond the direct effects on targeted stocks to allow for sustaining healthy ecosystems and provide a basis for the long-term sustainable development of fisheries (Pikitch et al., 2004; FAO 2003). When implemented as intended, EBFM can provide a variety of benefits to ecosystems (Fulton et al., 2019), but not without various challenges. Main challenges include gaps in data and knowledge of ecosystem structure and function, and there have been difficulties in identifying how to prioritize management decisions due to lack of useful tools (Astles and Cormier, 2018; Hobday et al., 2011). Today, different forms of ecological risk assessments are often used to assist in the implementation of EBFM (Gullestad et al., 2017; Samhouri et al., 2019; Smith et al., 2007).

Marine invertebrates are important to ecosystem structure and function and are affected by fisheries in many ways. This includes both direct and indirect effects from commercial harvesting, such as being caught and discarded, physical impacts from fishing gear, and food web effects. Furthermore, they may be more susceptible to fishing pressure than anticipated (Eddy et al., 2016). As the scope of invertebrate fisheries increases, and data deficiency makes population status difficult to monitor and set targets for, the risk of population collapse may also increase (Anderson et al., 2011). However, there is currently no ecological risk assessment that has looked specifically at invertebrates, as they commonly evaluate other taxa such as fish, marine mammals, and birds (e.g., Arrizabalaga et al., 2011; Cortés et al., 2010; Lin et al., 2020; Waugh et al., 2012). When included, invertebrates are assessed using the same cut-offs for life history parameters that indicate low-medium-high sensitivity to fishing pressure that are used for other taxa. This results in invertebrates often being classified as low risk relative to other species such as marine mammals and birds (Hobday et al., 2011). This, combined with the findings on invertebrate sensitivity to fishing pressure by Eddy et al. (2016), emphasizes the need for

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specific attention to marine invertebrates in an ecological risk assessment context.

The objective of this study is to examine the potential vulnerability of marine invertebrates to the pressures posed by Swedish west coast fisheries (the Kattegat, Skagerrak, and North Sea). This is done through adapting and applying productivity susceptibility analysis (PSA), a semi-quantitative ecological risk assessment tool, and evaluating available data from scientific observer programs. Both invertebrate species that are commercially targeted and those caught as unintended bycatch are included in the analysis. The overall aim is to highlight and inform the need for improved monitoring and management, as well as increased research, to decrease the risks to marine invertebrates and ecosystems introduced by Swedish fisheries.

2. Material and methods

2.1. Data

The study includes marine invertebrate species that have been documented in demersal trawl and creel fisheries operating on the west coast of Sweden (Fig. 1; Table 1). Two sources of information informed a species list:

i. Species recorded in data collected from onboard observer programs carried out at the Swedish University of Agricultural Sciences (SLU), collected as part of the European Union Data Collection Framework (Regulation (EU) 2017/1004), covering approximately 1% of the Swedish effort by demersal fleets (for further details, see Anon. 2019). The data used covers the Swedish west coast (ICES area 3a, broken down into the Skagerrak, the Kattegat and the North Sea; Fig. 1) and includes six demersal trawl fisheries and one creel fishery (Table 1). The fisheries were sampled between 2008 and 2019 and identified 33 invertebrates to the species level. Volumes were in the form of raised discards, i.e. an estimation of total discards for a combination of a species, year, area, and fishery (for further details, see Vanhee et al., 2020).

ii. Data from Ottosson (2008), adding an additional 60 species. These data were collected onboard two research vessels (benthic trawls), and one commercial shrimp trawl at 37 different sampling stations in the study area.

The full species list can be found in Appendix A.

2.2. Productivity susceptibility analysis (PSA)

Productivity susceptibility analysis (PSA) was initially developed to assess the potential vulnerability of different bycatch species in shrimp trawl fisheries (Stobutzki et al., 2001). Today, various approaches and applications exist for fisheries around the world (Hordyk and Carruthers, 2018). PSAs may assist in informing management decisions by prioritizing efforts on species and measures taken, but also by ranking research priorities through identifying knowledge gaps. The assessment

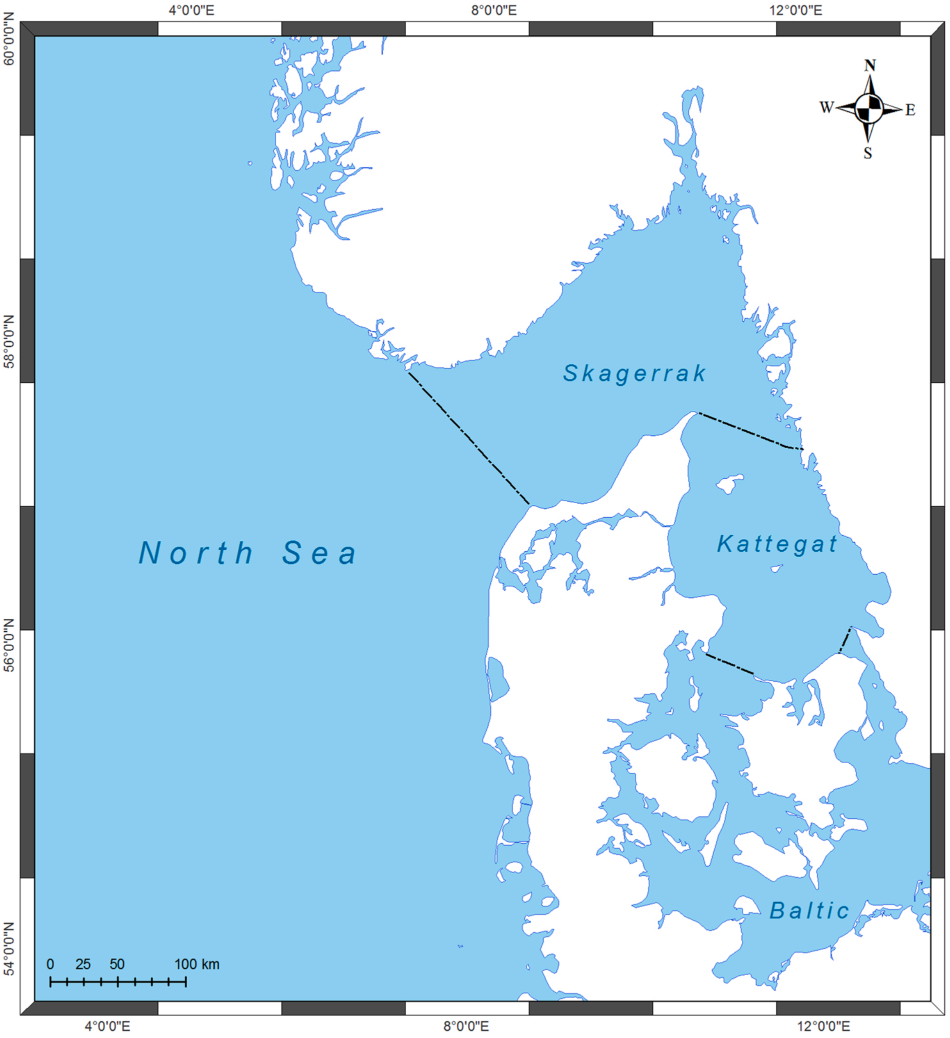

Fig. 1. Map of the North Sea, Skagerrak and Kattegat. Modified from ICES (2019).

Table 1
Fisheries on the Swedish west coast included in the analysis, where x indicates where the fishery is located (see map in Fig. 1) with PAS = creels and DEM = demersal trawls. The asterisk represents demersal trawls equipped with species-selective grids to sort out larger individuals (19 mm distance between bars for DEM 2- and 35-mm distance for DEM 6 respectively). Based on Hornborg et al. (2020).

Fishery Code	Skagerrak	Kattegat	North Sea	Depth range (m)	Min mesh size (mm)	Observer data	Main target species
PAS1	x	x		35–80	40	Yes	*Nephrops norvegicus*
DEM1	x	x		150–410	35	Yes	*Pandalus borealis*, mixed demersal fish
DEM2*	x	x		70–400	35	Yes	*Pandalus borealis*
DEM3			x	80–250	120	Some[a]	Gadoids
DEM4	x			45–240	90	Yes	*Nephrops norvegicus*, mixed demersal fish
DEM5		x		25–75	90	Yes	*Nephrops norvegicus*, mixed fish
DEM6*	x	x		30–175	70	Yes	*Nephrops norvegicus*

[a] Some observer trips exist from transboun dary fishing trips but the fishery is not within the regular sampling strata.

combines available information on an individual species' productivity (a set of life history attributes such as age at maturity) with a set of attributes for susceptibility to a certain fishery (related to risks with fishery interactions such as post capture mortality) to calculate the potential vulnerability of a species to a specific fishery. The overall vulnerability is then based on the Euclidean distance from the origin, where a score for a species' combined productivity attributes and a score for its susceptibility to fisheries produce separate coordinates on an axis. The risk level is then assigned through splitting the graph in three bins (low--medium-high). It is a coarse measure of vulnerability to overfishing, often measuring relative risk between species rather than absolute risk with the objective to prioritize species at high risk (e.g., Hobday et al., 2011); estimating absolute risk to a species would require more data available than is at hand when identifying the need for a risk assessment. To handle data-deficiency, PSA may use a precautionary approach by assigning high risk where there is a lack of data for an attribute (Hobday et al., 2011), but other approaches exist, such as decoupling vulnerability from data quality and instead provide best estimates for vulnerability with a separate data quality scoring (see e.g., Cope et al., 2011).

The methodology used here was based on previously published PSAs applied in data-deficient circumstances, i.e., assessing relative risks and applying a precautionary approach to risk (Hobday et al., 2011; Hornborg et al., 2020), with local adaptations. Following ERM (2017), if a species lacks data for three or more productivity attributes out of seven, overall risk for a species is then classified as being driven by data-deficiency, highlighting the need for further understanding.

2.2.1. *Productivity*

Values for productivity of the species were based on a variety of sources, prioritized according to Table 2. A strategy for prioritization was needed due to differences in life history estimates between sources, where a prioritization hierarchy enabled a standardized search procedure. If there was life history data missing after searching all the sources in Table 2, a dedicated literature search was done for the species (see Appendix B for all references used). When provided in the sources, conservative and local estimates were chosen, representing the most precautionary approach. This implies that when given a range, the estimate that corresponds to lower productivity was used (using the higher estimates of maximum age, size, age at maturity, size at maturity, and lower estimates of fecundity). Following a precautionary approach, if no data was found for a certain life history parameter, the species was assigned a high-risk score for the missing attribute (Hobday et al., 2011).

Colony size was used as size for colony-forming organisms, whereas for crustaceans, carapace length was used unless otherwise noted. For reproductive strategies, live bearers and hermaphrodites were classified as low productivity (as hermaphroditism has been shown to increase vulnerability; Roberts and Hawkins, 1999), demersal egg layers and brooding organisms (e.g. crustaceans) as medium productivity, and broadcast spawners as high productivity. The cut-offs for low, medium, and high productivity for each life history attribute were calculated by splitting the species into three relatively equal sized bins based on the range the attribute exhibited (Table 3), following the procedure of Hobday et al. (2007).

The combined productivity score P for a species represents the average value for all the species attributes, where each attribute is assumed to be equally important.

Table 2
Main sources for productivity data, listed in order of how they were prioritized. Searches were done between October 3, 2020 and November 13, 2020.

Prioritization	Source	URL or DOI	Species
1	Swedish Species Initiative	https://artfakta.se/artbestamning	All
2	SeaLifeBase	https://www.sealifebase.se/search.php	All
3	The Marine Life Information Network (MarLIN)	https://www.marlin.ac.uk	All
4	IUCN Red List	https://www.iucnredlist.org	All
5	FAO FishFinder	http://www.fao.org/fishery/species/search/en	All
6	Jereb et al., (2015)	https://doi.org/10.17895/ices.pub.5493	Cephalopods
7	Jereb and Roper, (2010)	http://www.fao.org/3/i1920e/i1920e.pdf	Cephalopods
8	Holthuis, (1980)	http://www.fao.org/3/ac477e/ac477e00.htm	Prawns and Shrimp

2.2.2. *Susceptibility*

The same choice of attributes was used as in ERM (2017). The approach for estimating availability was adapted to the study area, with global distribution corresponding to low susceptibility, distribution in the northern hemisphere medium susceptibility, and distribution only in Swedish waters high susceptibility (Table 4). We assume that all 93

Table 3
Productivity attributes and cut-offs for low, medium, and high-risk scores.

Attribute	Low Productivity (score 3 = high risk)	Medium Productivity (score 2 = medium risk)	High Productivity (score 1 = low risk)
Maximum age	> 9 years	3.5 – 9 years	< 3.5 years
Maximum length	> 15 cm	7 – 15 cm	< 7 cm
Age at maturity	> 4 years	1.3 – 4 years	< 1.3 years
Size at maturity	> 6 cm	3 – 6 cm	< 3 cm
Fecundity (eggs per year, lifetime)	< 1277 eggs	1277 – 20,000 eggs	> 20,000 eggs
Reproductive Strategy	Live bearer, hermaphrodite	Demersal egg layer, brooder	Broadcast spawner
Trophic level	> 3.5	2.99 – 3.5	< 2.99

Table 4
Susceptibility attributes and the cut-offs used for low, medium, and high-risk classifications. Absence of information was classified as high risk.

Attribute	Low Susceptibility (score 1 = low risk)	Medium Susceptibility (score 2 = medium risk)	High Susceptibility (score 3 = high risk)
Availability	Global	Northern hemisphere	Endemic to Sweden
Post capture mortality (PCM)	< 33%	33 – 66%	> 66% and commercial species
Encounterability	< 0.33 depth overlap	0.33 – 0.66 depth overlap	> 0.66 depth overlap
Selectivity	Max. size < mesh size	Max. size = 1–2 times mesh size	Max. size > 2 times mesh size

species included in the PSA could be caught in all fisheries included in the analysis, since all of the fisheries operate in the same area as the species occur and pose different potential risk (based on e.g., depth and mesh size). It also follows the approach of assessing more rare and sensitive species in the guide to PSA by ERM (2017), i.e., including all species that are present in an area.

Encounterability was based on a combination of fishery-specific and species data in the form of depth overlap of fishing depth range and species depth distribution. High encounterability equaled a depth overlap of more than 66%, medium between 33% and 66%, and low less than 33% (Table 4). Lack of depth overlap data (missing depth distribution for a species) was classified as high risk for encounterability. The same procedure was applied to all species, demersal and pelagic (i.e., there was no habitat override assigning low risk for a pelagic species in a demersal fishery).

Selectivity was determined using a combination of species characteristics, fishing gear design, and expert opinion related to the studied fisheries and different selectivity of the gears used. The general formula follows Hobday et al. (2007): high susceptibility was assigned when species maximum size was more than two times larger than the mesh size used in a fishery, medium when maximum size was 1–2 times mesh size, and low when maximum size was less than mesh size (Table 4). Where maximum size information was unavailable, susceptibility was classified as high to be precautionary.

For post-capture mortality (PCM), a literature search was done specific to marine invertebrates in trawl and creel fisheries (references can be found in Appendix B). Where data was available and provided as a range, the maximum value in the reported range for PCM was used to allow for conservative estimates. Short-term mortality was used over long-term mortality when different estimates were available. Generalizations across similar species and taxa were made where needed and justified, e.g., true crabs were grouped together (supported by e.g., Bergmann and Moore, 2001a; Bergmann and Moore, 2001b; Depestele et al., 2014), to mitigate the high level of data deficiency for PCM. Species were then sorted into low, medium, and high risk where mortality under 33% equals to low PCM, 33–66% medium, and above 66% high PCM (Table 4). Species were automatically assigned high PCM if they were a targeted commercial species (which are generally landed) or where data and expert opinion were not available. For creel PCM, lack of data required the development of a workflow to determine a ranking using expert opinion: high risk for commercial species or species where data was missing for both trawl and creel PCM; low risk if data showing PCM from trawls was low; for the remaining species, PCM was set at one level lower for creels than for trawls.

For the combined susceptibility score S, the calculation differs to the calculation for the combined productivity score P. This is motivated from single attributes for estimating S may be more important to the overall score (e.g. a low PCM). Susceptibility is calculated using Eq. 1:

$$S = \sqrt[4]{A * E * s * PCM} \quad (1)$$

where S represents the susceptibility score, A availability, E encounterability, s selectivity, and PCM post capture mortality.

2.2.3. *Vulnerability*

Different equations exist to estimate the final PSA score V, which indicates a species' potential vulnerability to the fishery. We applied the 'standard equation' (Hordyk and Carruthers, 2018), which is used to evaluate relative risks for data-deficient, bycaught species rather than determining actual risks for targeted species:

$$V = \sqrt{P^2 + S^2} \quad (2)$$

where P is the combined productivity score of the species and S is the combined susceptibility score. The score for V is then translated into relative risk level for the species to the fishery based on the Euclidean distance of the data point from the origin of a plot, here assuming the origin is at 0, by dividing into equal thirds: low risk species $V < 2.64$; medium risk 2.64–3.18; and high risk >3.18 respectively. Note that the origin is assumed to be at 1 in many applications of PSA, e.g., for the 'extended equation' (Hordyk and Carruthers, 2018). Here we chose to apply the 'standard equation' and assume origin at 0 to allow for our results to be coherent with findings of a previous study on the vulnerability of the fish community in the same fishing area (Hornborg et al., 2020).

2.2.4. *Data quality assessment*

For a data quality assessment of the attributes underpinning the PSA, data inputs were scored following Patrick et al. (2010) with specific definitions in Table 5. Additional references used to motivate data quality scoring for attributes taken from databases (with information on e.g., how data is collected and reviewed), can be found in Appendix B.

2.3. *Trend analysis of discard data*

Quantitative data from the observer program was further examined in terms of volumes and trends for different species, and if available data could support or dismiss the identified vulnerability of the PSA in terms of actual impacts on species, including variables that influence catch volumes. However, robust statistical analysis (linear models) could not be performed due to the data being too uneven and having too small sample sizes for the parameters of interest. The one exception was the commercial species *Nephrops norvegicus*, which is included in a stock assessment framework at the International Council for the Exploration of the Sea (ICES). Not even *Pandalus borealis*, the other important commercial species that also has a stock assessment, could be analysed

Table 5
Data quality tracking used, based on Patrick et al. (2010).

Data quality score	Description	Example (for websites, see Table 5)
1	Best data, e.g. substantial data collected and analysed for the species, global and local databases with transparent data collection and review processes.	Swedish Species Initiative ; SeaLifeBase (2020); The Marine Life Information Network ; IUCN Red List (2020); FAO FishFinder ; Jereb et al.(2015); Jereb and Roper (2010)
2	Adequate data, e.g. more limited data collection and analysis.	Holthuis (1980); SeaLifeBase (2020) on trophic levels;
3	Limited data, e.g. high variation of estimates and information may be based on studies of similar taxa.	SeaLifeBase (2020) on trophic levels of similar taxa; PCM of similar taxa
4	Very limited data, e.g. based on expert opinion or general literature review that is not region- or species specific.	PCM based on expert opinion
5	No data.	

in terms of catch volumes for the parameters investigated, i.e., year, area and fishery (based on Anderson and Burnham, 2002).

Due to the inability to perform quantitative analysis on actual impact on invertebrate populations from fisheries for 92 out of 93 species, PSA results of all species were instead cross-checked against status on the Swedish IUCN Red List of Threatened Species (Artdatabanken, 2020). This national assessment is updated every five years, led by the Swedish University of Agricultural Sciences (SLU) following the IUCN guidelines (IUCN, 2001) and their regular updates (e.g., IUCN, 2022). The data originate from national and regional marine monitoring programs and is analyzed by taxonomic expert groups (Gärdenfors, 2001).

3. Results

3.1. Data quality

Of the 93 species included in the PSA, 56% (52 species) could be categorized as data-deficient based on lack of available information for productivity attributes, with 29% only having one or two known attributes, and two species had no known attributes at all (Table 6).

Data quality for the productivity attributes identified was generally high, relying on specific data for the species to a large extent (for full results, see Appendix C). There was however a considerable variability in data quality between species and attributes, where max length was the attribute with best available data (1.1±0.6 for all species), followed by reproductive strategy (2.2±1.8), although the latter being more variable between species. Age at maturity had the overall poorest data quality (3.7±1.8), followed by size at maturity (3.4±1.9). For the susceptibility attributes, post-capture mortality had the worst data quality, especially for creels (4.4±0.5, but also for trawls (3.6±1.4), highlighting a major and important uncertainty in the risk assessment.

3.2. Risk assessment

The number of species at potential high risk varied between the fisheries, but an overall lower number of high and medium risk species were seen among species that were not classified as data-deficient (Fig. 2), indicating that risk levels are partially driven by data-deficiency.

Among the 41 species that were not data-deficient, three species were classified as being associated with high risk for all seven fisheries evaluated (Table 7). These included two of the commercial invertebrate species that are targeted in the area (*Homarus gammarus, N. norvegicus*,) as well as a by-catch species of potential commercial value (*Loligo forbesii*). However, all three species are categorized as Least Concern (LC) on the Swedish IUCN Red List of Threatened Species, indicating that no alarming declines are seen. There were also 11 non-data-deficient species that were classified as being associated with low risk across all fisheries (Table 7). Most of these species are also categorized as LC, although one species is red-listed (*Munida rugosa*; NT). Overall, the PSA indicates that most echinoderms appear to be less vulnerable to being caught in the studied fisheries, whereas crustaceans and cephalopods exhibit higher variability, including many species being associated with medium to high risk.

Among the 15 data-deficient species classified as being at high risk in all fisheries (Table 8), two of the species (*Aega crenulata* and *Trischizostoma raschii*) had missing information for all seven life history attributes. These two species have not been evaluated by the Swedish Red List. Three of the data- deficient species that were classified as high risk in all fisheries were red-listed (*Funiculina quadrangularis*, VU; *Spatangus purpureus,* NT; *Spatangus raschi*, CR).

Of the 93 studied invertebrate species, 17 species (18.3%) are categorised as red-listed on the Swedish IUCN Red List (DD, NT, VE, EN, CR). Of these, 11 species (65%) were also considered to be data deficient for the PSA. For 14 of the species (*Abra nitida, Asterias rubens, Astropecten irregularis, Brissopsis lyrifera, Carcinus maenas, Crepidula fornicata, Echinocardium cordatum, Gattyana cirrhosa, Liocarcinus depurator, Liocarcinus holsatus, Munida rugosa, Ophiothrix fragilis, Pisidia longicornis, Platynereis dumerilii*), potential risks from being caught in all the studied fisheries were found to be low, regardless of data availability. Full results of the PSA can be found in Appendix D.

Available onboard observer data are very uneven and dominated by certain groups. At phylum level, arthropods dominate the discard data records. Within the whole dataset, most of the observer data records are based on *N. norvegicus* and *P. borealis*. Few data points and minimal discard volumes are found in the onboard observer data for non-commercial cnidarians, echinoderms, and molluscs. The additional species from Ottoson (2008) predominantly comprised of species belonging to the phyla Echinodermata (20 species) and Arthropoda (17 species) and included species belonging to phyla that had not been reported at all in observer data such as Porifera and Cnidaria (for full details, see Appendix A).

Table 6
Breakdown of the number of species with each number of productivity attributes missing.

Number of Attributes Missing	0	1	2	3	4	5	6	7
Number of Species	13	17	11	7	16	20	7	2

4. Discussion

This study has found that data deficiency is widespread when assessing potential risks from fisheries' interactions with marine invertebrates. Many of the included species showed high vulnerability to fisheries; however, the outcome of ecological risk assessments is sensitive to both methodological choices and data availability. Firstly, results are influenced by widespread data-deficiency of basic life history traits, even in a relatively well-researched area such as the eastern North Sea region analyzed here. The PSA design takes a precautionary approach towards protecting species, where the approach applied here assigns high risk for an attribute if there is lack of data on a life history trait, contributing to false positives (see e.g., Zhou et al. 2016 and Hordyk and Carruthers 2018 for more comparisons between methods). Secondly, the vulnerability estimated here is an assessment of relative risk amongst the invertebrates studied, i.e., identifying the invertebrate species among those included that are most vulnerable to the different Swedish fisheries. The high-risk commercial species that are targeted in Swedish fisheries have management regulations in place, but high-risk commercial by-catch species may require extra attention to decrease potential risks. Thirdly, based on available records on catches, only 93 species were included in this study – out of the ~6000 marine invertebrate species documented in the area (Hansson, 1994). Most invertebrates are not necessarily caught in fishing gears, but the discrepancy in the number of species listed in the independent research study (Ottosson, 2008) compared to the onboard observer program indicates that fisheries may interact with far more species than have been registered in monitoring programs. The master thesis (Ottosson, 2008), which was a limited study (37 hauls performed by three vessels belonging to three different fisheries), identified 60 more species than what was recorded in continuous observer data collection between 2008 and 2019. To this end, PSAs as performed here are a starting point to identify and prioritize subsequent actions, which could include both fishing restrictions or/and further data collection (ERM, 2017; Hobday et al., 2011). The data quality analysis showed that gaps in data were especially prevalent for reproductive biology (i.e. age and size at maturity and fecundity) and post-capture mortality, suggesting that further research in these areas should be prioritized. Overall, this study highlights the need to pay more attention to marine invertebrates in monitoring programs as well as drive research to further the understanding of invertebrate species' life histories and sensitivity to fishing pressure to proceed in implementing ecosystem-based fisheries

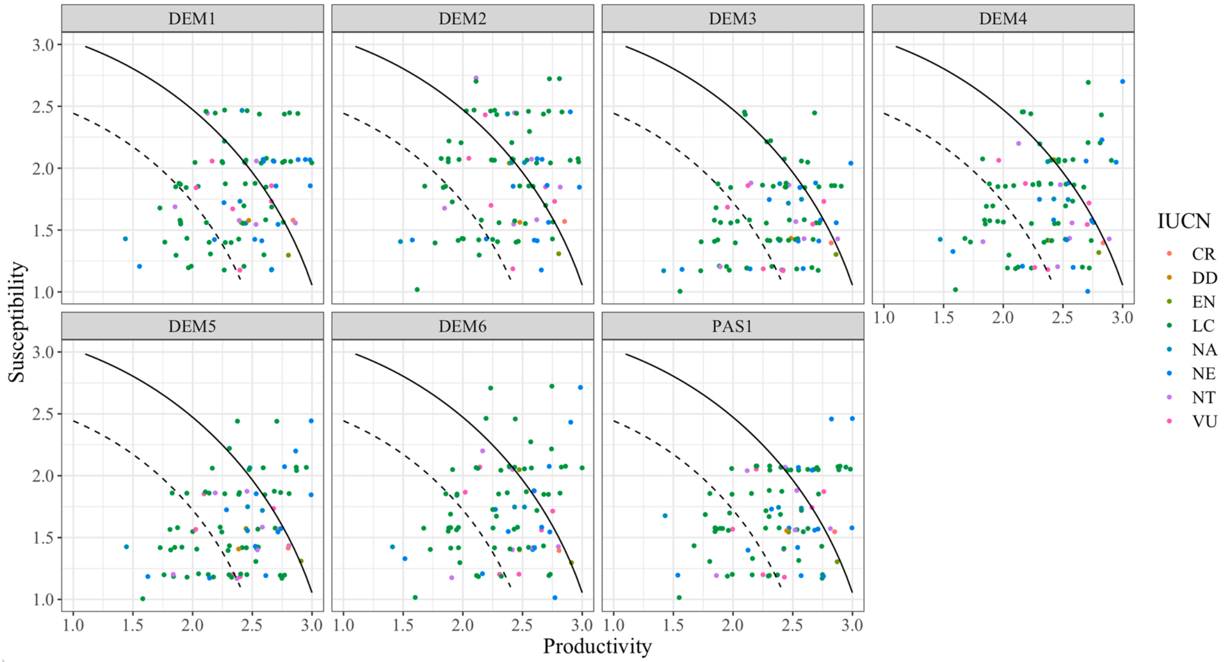

Fig. 2. PSA results for the 93 species assessed, along with data availability and Swedish IUCN ranking for each species. All fisheries are assumed to interact with all 93 species. The dashed line represents the cutoff between low and medium risk and the solid line represents the cutoff between medium and high risk.

management.

Two of the trawl fisheries, *Pandalus borealis* (DEM2) and *Nephrops norvegicus* (DEM6), are equipped with species-selective grids. These gears are effective in sorting out vulnerable fish species (Hornborg et al., 2013) but may still pose high risk to invertebrates given it is a targeted invertebrate fishery. Furthermore, many vessels in the *P. borealis* fishery voluntarily use larger mesh sizes than the minimum requirement of 35 mm (many vessels use 45 mm mesh, some even 52 mm; Hornborg and Mann, 2019). Overall, factors that correlate with low risk in a PSA include larger mesh sizes, lower post-capture mortality, and a more limited depth range for the fishery – with the creel fishery being favorable for all these factors, especially post-capture mortality. It would have been expected that the creel fishery would pose lower risk than the bottom trawl fisheries based on e.g., discard volume and benthic impact (Hornborg et al., 2016; Ziegler and Valentinsson, 2008). However, the three risk levels applied and the semi-quantitative approach of a PSA may not properly reflect those differences between fishing methods. Post-capture mortality is the variable in the PSA that best accounts for the differences between the creel and trawl fisheries, but this difference was not visible in the results, likely due to the prevalence of data-deficiency for invertebrate species. Improved data collection on non-commercial species in observer programs may further our understanding on actual catch volumes.

4.1. *Invertebrate discard volumes and sampling*

Global trends in fishery discards exhibit decreasing volumes since the 1980 s, influenced by changes in fishing gear design to limit bycatch, discard bans, as well as changes in market demand (Gilman et al., 2020; Kelleher, 2005; Zeller et al., 2017). The studied fisheries have since 2008 been affected by legislative changes introduced at the European Union (EU) level. These changes were implemented to decrease discard volumes through the use of mandatory selective devices and a gradual implementation of the landing obligation for commercial species (European Commission, 2021; Regulation (EU) 2019/1241; Valentinsson and Nilsson, 2015). With this policy objective, EU fisheries management also decreased the minimum landing size of *N. norvegicus* from 40 to 32 mm in 2016, decreasing the proportion of the catch that is discarded (Regulation (EU) 2015/2440; ICES, 2020a,b). Discard volumes of *P. borealis* have also declined as an effect of changes in management, market, and fishing practices, where the size of the fishing fleet declined between 2009 and 2012 – or a reduction of nearly 50% over the last decade (ICES, 2020c; SwAM, 2014).

The data from onboard observer programs was not sufficient to quantitatively analyze trends in non-commercial species. Generally, onboard observer programs are limited in their scope and may be biased (Benoît and Allard, 2009; Faunce and Barbeaux, 2011; Maxwell and Jennings, 2005). Data records can be affected by deployment (lack of randomization in the assignment of observer coverage, however considered for the Swedish observer program) and observer effects (changing fishing behaviors with observers present). Although observers have a standardized protocol to follow and are trained to sample everything that is brought on board, considerably more species were found in the data from Ottosson (2008) compared to the onboard observer discard data. Ottosson (2008) was also more thorough in the identification of the catch, as everything was identified to a species level, whereas in the onboard observer data, there were varying levels of taxonomic resolution (some organisms were only identified to a phylum level). Protocols for sampling and recording non-commercial invertebrates are less stringent in current onboard observer programs, which are focused on commercial species, and are thus more dependent on the time, interest, and knowledge of the observer onboard. Many trips only have indicative records, such as a volume of total invertebrates and information on dominant species.

Besides changes in regulations and fishing gears, and limited monitoring, non-present or declining discards of non-commercial invertebrates that are extra sensitive to trawl effects, such as corals and sponges, may also be caused by depletion (e.g., Morrison et al., 2020; Downie et al., 2021). Due to lack of baselines from before onset of demersal trawling, it is unknown to which extent this influence trends in discard volumes, indicate differences in abundances between species, or even long-term effects of fishing activities in the area. For example, Obst et al. (2018) showed that many invertebrate species in the Skagerrak and Kattegat have experienced negative trends over the last decades, with some polychaetes, a barnacle (*Verruca stroemia*), an echinoderm (*Psammechinus miliaris*), and a mollusc (*Buccinum undatum*) showing the

Table 7
Potential risk levels for the 41 species not categorized as data-deficient. *Commercial species that is monitored under national or international fishery management in the area.

Species group	Scientific Name	DEM 1	DEM 2	DEM 3	DEM 4	DEM 5	DEM 6	PAS 1	IUCN status
Ascidia	*Ascidiella scabra*	High	High	Med	Med	Med	Med	Med	LC
Bivalvia	*Aequipecten opercularis*	Low	Med	Low	Low	Low	Low	Low	LC
	Arctica islandica	Low	Med	Low	Low	Low	Low	Low	LC
	Echinocardium cordatum	Low	Low	Low	Low	Low	Low	Low	LC
	Modiolus modiolus	Med	Med	Low	Med	Low	Med	Low	VU
	Pecten maximus	Med	Med	Med	Med	Low	Med	Low	LC
Cephalopoda	*Alloteuthis subulata*	High	High	Med	High	High	High	High	NA
	Eledone cirrhosa	Med	High	Med	High	Med	High	Med	EN
	Illex coindetii	Med	Med	Med	Med	Med	Med	Med	NE
	Loligo forbesii	High	High	High	High	High	High	High	LC
	Rossia macrosoma	Med	Med	Low	Low	Low	Low	Med	LC
	Sepietta oweniana	Low	Med	Low	Low	Low	Low	Low	LC
	Sepiola atlantica	Low	Low	Low	Med	Low	Med	Low	LC
	Todarodes sagittatus	Med	High	Med	Med	Med	Med	Med	NA
	Todaropsis eblanae	High	High	Med	Med	Med	Med	Med	NA
	Loligo vulgaris	High	High	High	High	Med	Med	Med	LC
Crustacea	*Cancer pagurus**	High	High	High	High	Med	Med	Med	LC
	Carcinus maenas	Low	Low	Low	Low	Low	Low	Low	LC
	*Homarus gammarus**	High	High	High	High	High	High	High	LC
	Liocarcinus depurator	Low	Low	Low	Low	Low	Low	Low	LC
	Lithodes maja	Med	Med	Med	Med	Med	Med	Med	LC
	*Nephrops norvegicus**	High	High	High	High	High	High	High	LC
	*Pandalus borealis**	High	High	Med	Med	Med	High	High	NT
	Crangon allmanni	High	High	Med	Med	Med	Med	Med	NT
	Dichelopandalus bonnieri	Med	High	Med	Med	Med	Med	Med	VU
	Pandalus montagui	High	High	High	High	Med	High	Med	LC
	Pasiphaea multidentata	High	High	Med	Med	Med	Med	High	LC
	Pasiphaea sivado	Med	Med	Low	Med	Med	Med	Med	LC
	Liocarcinus holsatus	Low	Low	Low	Low	Low	Low	Low	LC
	Munida rugosa	Low	Low	Low	Low	Low	Low	Low	NT
	Pisidia longicornis	Low	Low	Low	Low	Low	Low	Low	LC
Echinodermata	*Asterias rubens*	Low	Low	Low	Low	Low	Low	Low	LC
	Brissopsis lyrifera	Low	Low	Low	Low	Low	Low	Low	LC
	Ophiothrix fragilis	Low	Low	Low	Low	Low	Low	Low	LC
	Strongylocentrotus droebachiensis	Low	Med	Low	Low	Low	Low	Low	LC
	Trachythyone elongata	Med	High	High	High	High	High	Med	LC
Gastropoda	*Buccinum undatum*	Med	Med	Med	Med	Med	Med	Med	LC
	Crepidula fornicata	Low	Low	Low	Low	Low	Low	Low	NA
Annelida	*Aphrodita aculeata*	Med	Med	Med	Med	Med	Med	Med	NE
	Platynereis dumerilii	Low	Low	Low	Low	Low	Low	Low	NE
Cnidaria	*Alcyonium digitatum*	High	High	Med	High	High	High	High	LC

Table 8
Species identified as being both at high risk in all the studied fisheries and data deficient in terms of known attributes for productivity. IUCN category according to the Swedish Red List is also included (SLU Artdatabanken, 2020).

Species	IUCN	Phylum (subphylum)	Known productivity attributes
Pasiphaea tarda	LC	Arthropoda (Crustacea)	3
Aega crenulata	NE	Arthropoda (Crustacea)	0
Alcyonidium diaphanum	NE	Bryozoa	2
Ascidia virginea	LC	Chordata (Tunicata)	3
Funiculina quadrangularis	VU	Cnidaria	4
Mesothuria intestinalis	LC	Echinodermata (Holothuroidea)	1
Neanthes fucata	NE	Annelida (Polychaeta)	2
Parastichopus tremulus	LC	Echinodermata (Holothuroidea)	1
Pennatula phosphorea	LC	Cnidaria	4
Polycarpa pomaria	LC	Chordata (Tunicata)	2
Securiflustra securifrons	NE	Bryozoa	2
Spatangus purpureus	NT	Echinodermata (Echinoidea)	1
Spatangus raschi	CR	Echinodermata (Echinoidea)	1
Suberites ficus	NE	Porifera	2
Trischizostoma raschii	NE	Arthropoda (Crustacea)	0

strongest declines. Of these species, only *B. undatum* was recorded as caught in the studied fisheries, and thus included (medium risk in all the studied fisheries).

4.2. Invertebrates and risk assessments

The North Sea and adjacent areas are arguably one of the best studied marine areas in the world (Hestetun et al., 2020). The high degree of invertebrate species lacking basic information on life history traits is problematic, but perhaps not surprising in a global perspective (Anderson et al., 2011; Boenish et al., 2022). The general data-deficiency is alarming since invertebrates may be more susceptible to fisheries than e.g. small pelagic fish, and fishing effects on invertebrates are less understood (Eddy et al., 2016). The findings from this study could be compared with a PSA of the same fisheries assessing risk levels for the fish community (Hornborg et al., 2020). Of the 145 assessed fish species, the average value for known life history attributes was six out of seven – with 46% having all attributes for productivity known, and only 4% had merely 1–2 known attributes. Furthermore, a slightly higher but similar proportion of species were red-listed – over 18% for the assessed invertebrates and 17% for the fish species. Given similar threat levels but with more widespread data-deficiency for the invertebrates, this arguably highlights the urgency for more research and data collection to improve knowledge and decrease risks.

This PSA addressed direct fishery interactions with invertebrates, not indirect effects through e.g., benthic sediment disturbance and habitat degradation (e.g., Sala et al., 2021). When assessing risks invertebrates, that also includes sessile or sedentary species, methodological complexity exists. Species such as the tall sea pen *Funiculina quadrangularis* (VU) was found to be associated with high risk in all fisheries. This shows some coherence between potential risks and threat level – but the species was classified as data-deficient in the PSA. Furthermore, no difference in risk could be observed between creels and demersal trawls although a large difference in actual impact would be expected (Eno et al., 2001). Another example shows more incoherence between the estimated vulnerability to fishing and threat status. The PSA classified *Modiolus modiolus* (VU) as being associated with low risk for two demersal trawl fisheries. The current threat categorization may indicate depletion that is directly or indirectly driven by fisheries (see e.g., Cook et al., 2013) while the PSA failed to pick up the potential risk due to e.g., many favorable life history attributes. The susceptibility attributes applied here are also more designed to assess catch-related interactions, which may not be relevant for all species in this diverse group. Vulnerability to fisheries for some invertebrate species groups may better be addressed through other risk assessment designs, where there are PSAs developed to examine the impacts of demersal trawling on seabed habitats (e.g., Pitcher et al., 2017; Williams et al., 2011), but they are not widely used.

Determining which invertebrates that should be included in a PSA to assess risks from potential bycatch interactions, as well as choosing the proper risk assessment methodology for this diverse group (species- or habitat based), is not straightforward. Motivated from having previously been caught in fishing gears, all species included in this study were treated as having the potential to interact with all demersal fisheries where there is a depth overlap. This is an approach commonly applied to be precautionary for fisheries where observer data is lacking. Where observer data exists, one way to minimize the potential false positives from this assumption is to only include species present in collected data for the specific fishery. However, this approach likely results in rare and threatened species not being properly represented due to monitoring programs often failing to detect declines of these species (Maxwell and Jennings, 2005). To address this potential bias, some ecological risk assessments include all threatened species present in an area (e.g., ERM, 2017), although this increases the risk for false positives. Furthermore, applying encounterability as a depth overlap, as has been done in this study, could be refined to consider potential differences between benthic and pelagic species, sessile and mobile species, and infauna and epifauna. For example, pelagic species may not be caught in a demersal trawl fishery. One way to address this would be to add in habitat overrides, where e.g. a benthic species is assumed to have a low encounterability with a pelagic species regardless of degree of depth overlap.

Finally, ecological risk assessments are beneficial in that they are easily adaptable, scientifically robust, and can be adapted to a specific fishery, the amount of data available, and management objectives and goals (Hobday et al., 2011). However, despite PSA being a widely used tool, there have also been criticisms. Hordyk and Carruthers (2018) suggest that PSA performs poorly when the potential vulnerability of a species is not very high or very low. The way that vulnerability is calculated will generally also result in an average score more often than high or low vulnerability scores, and that when plotted, the points will cluster around the center (Grewelle et al., 2021). This emphasizes the need to further develop risk assessment methodologies. A new methodology suggested by Grewelle and colleagues (2021) would also allow for comparisons across studies, which can contribute to more comprehensive data. This could be an important step in further evaluating the overall risk fisheries pose to ecosystems, as PSA does not allow for easy comparisons across studies due to its sensitivity to methodological choices (such as cut-off values and attributes used), i.e., it is a measure of relative risk for species within a study not between different studies unless methodological choices are harmonized. As an example, the specific cut-offs for low-medium-high risk applied in this study (based on invertebrates only) is quite different to the more generic cut-offs covering vertebrates (Hobday et al., 2011). The cut-offs for high risk applied here for the attributes maximum age, fecundity, age and size at maturity, are below the generic cut-offs for low risk for the same attributes. This implies that when assessed alongside vertebrates, invertebrates are likely to be assessed as having low vulnerability. Still, in terms of actual risks, many of the species are red-listed – making it imperative to further our understanding on how to properly assess risks and mitigate potential pressures on invertebrates from fisheries.

5. Conclusion

This study has highlighted a high degree of data-deficiency for assessing marine invertebrate productivity and susceptibility to fisheries in a well-studied European fishing area. Despite onboard observer programs being an important part of fisheries management, recording catches of non-commercial species is not mandatory under EU legislation but only done as an expanded collection effort. Through using arguably the best available fisheries data at hand in an EU context, the study illustrates that observer data collection for fisheries' interactions with non-commercial invertebrates is limited. Further research should be done to collect data, with priority on life history traits concerning the data-deficient species. For the species where data-deficiency was of less concern, species that were classified as medium and high risk should be prioritized for management action such as improved discard data collection and quantitative assessments on trends. Future research efforts should also entail developing risk assessment methodologies suitable for fisheries interactions with marine invertebrates.

CRediT authorship contribution statement

Daniel Valentinsson: Writing – review & editing, Validation, Investigation, Data curation. **Thomas G. Dahlgren:** Writing – review & editing, Validation, Supervision. **Sara Hornborg:** Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Linnéa Morgan:** Writing – review & editing, Visualization, Methodology, Investigation, Formal analysis, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fishres.2024.106982.

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