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Ecosystem risk from human use of ocean space and resources: A case study from the Norwegian coast

Johanna M. Aarflot[a,*], Vilde R. Bjørdal[a], Katherine M. Dunlop[b], Marina Espinasse[a], Bérengère Husson[a], Ulf Lindstrøm[c,d], Felicia Keulder-Stenevik[a], Kotaro Ono[e], Anna Siwertsson[a,1], Mette Skern-Mauritzen[a]

[a] Ecosystem Processes, Institute of Marine Research, Bergen, Norway
[b] Benthic Resources, Institute of Marine Research, Tromsø, Norway
[c] Marine Mammals, Institute of Marine Research, Tromsø, Norway
[d] Institute of Arctic and Marine Biology, UiT the Arctic University of Norway, Norway
[e] Fisheries Dynamics, Institute of Marine Research, Bergen, Norway

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ABSTRACT

Coastal and adjacent shelf waters are generally highly productive ecosystems harboring important ecological processes and exposed to a range of anthropogenic pressures from land-based and marine sectors. Ensuring that the cumulative pressures from human activities do not cause unacceptable, permanent harm to the ecosystem is challenging but crucial for sustainable management of these regions. Linkage frameworks and ecological risk assessments have proven to be useful tools for holistic evaluations of cumulative human pressures as a guide to managers and policy makers for prioritization of risk factors. Here, we present the first holistic assessment of ecosystem risk from human activities along the Norwegian coast. Pressures from coastal sectors are identified and weighted by the exposure to and potential impact on ecosystem components following the ODEMM (Options for Delivering Ecosystem-based Marine Management) framework. We focus on four coastal regions with contrasting scales of human activities. Two southern regions with multiple anthropogenic activities are associated with higher cumulative risk of negative impacts compared to northern areas where less extensive activities have a lower potential of harming the coastal ecosystems. Despite latitudinal differences in human use of the coastline, the pressures and ecosystem components associated with the greatest risk of cumulative impacts are relatively similar between the regions. Contaminants and underwater noise stand out as high-risk pressures, associated with multiple sectors with a high spatiotemporal footprint and with the potential to negatively impact a range of ecosystem components. Nevertheless, a confidence assessment also highlights the need for more in-depth analysis on the input, spread and effect of these pressures on coastal ecosystems. We discuss strengths and weaknesses of the risk assessment framework and suggest new directions which may enhance the utility and uptake of such assessments for sustainable management of coastal ecosystems.

1. Introduction

Globally, coastal waters and adjacent shelves represent some of the most productive and economically valuable marine ecosystems (Barbier et al., 2011; Costanza et al., 1997; Ryther, 1969). In addition to harboring important ecological processes like spawning, feeding and nursery grounds for key fisheries and other marine resources, coastal regions serve important functions such as nutrient cycling, disturbance regulation, detoxification of human waste, carbon storage and key sites for marine food and renewable energy production (DNV, 2023; Lu et al., 2018; Pauly and Christensen, 1995; Sætre et al., 2007). Furthermore, coastal zones are often heavily urbanized (e.g. in Europe, almost half of the population resides within 100 km from the coastline) and coastal populations both depend on and impact coastal marine ecosystems through land-based and maritime activities (Villasante et al., 2023). The cumulative pressures from human activities and climate change have

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[*] Corresponding author. Postboks 1870 Nordnes, 5817, Bergen. Norway.
E-mail address: johanna.aarflot@hi.no (J.M. Aarflot).
[1] Current address: Akvaplan-niva, Tromsø, Norway.

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been increasing over the 21st century e.g. in terms of fishing, land-based pollution, coastal development, shipping and mariculture, and tend to be higher in coastal regions compared to the open ocean (Duarte et al., 2008; Halpern et al., 2015, 2019). Sustainable use of coastal waters requires managers and policymakers to ensure that human activities and their impacts on coastal ecosystems are within the limits of what the system can handle, for avoiding permanent damage and leaving future generations with all options open as for how they wish to utilize the ocean (Bailey and Hopkins, 2023). This requires information on how all activities impose pressures on and potentially harm ecological components of the coastal ecosystems (Borja et al., 2016) and is a substantial task of collating and synthesizing a wide range of knowledge on human-ecological interactions.

Over the next decades, the intensity and diversity of our cumulative pressures on the ocean will likely increase (Halpern, 2020; Jouffray et al., 2020). Coastal nations are becoming increasingly dependent on marine resources and maritime activities, a trend referred to as the Blue Economy, and we have major expectations for the ocean to sustain the future growth of humanity (Jouffray et al., 2020; World Bank, 2017). Under the Blue Economy, a range of "blue" industries are predicted to grow and intensify, the most important being coastal mariculture, tourism, offshore wind and shipping (Turschwell et al., 2022). Humans will therefore occupy and utilize an increasingly larger part of the ocean over the next decades and much of the growth will take place in already busy, shallow nearshore regions (DNV 2023; Villasante et al., 2023), such as permanent installations for marine food and renewable energy production projected to occupy 7 times larger areas than today by 2050 (DNV, 2021).

When we increase and diversify our use of (and pressure on) the ocean, it becomes even more challenging for managers and policymakers to keep track on the cumulative environmental impact of our actions. Indeed, defining sustainability criteria across marine sectors to move towards sustainable coastal management has proved to be challenging (Blasiak et al., 2014; Halpern, 2020). While frameworks and goals such as the Ocean Health Index and UN Sustainability Development Goals can be used to evaluate sustainability for larger oceans, there is currently no clear pathway for how such broad criteria can be translated to smaller-scale, coastal regions of a single country such as Norway (a process called "localization", Dankel et al., 2022; Delgado-Serrano and Ramos, 2015).

Norway is a country for which the Blue Economy and maritime activities are a cornerstone of the national economy (Jakobsen et al., 2018; Kvamstad-Lervold et al., 2019). The country is a leading supplier of offshore fossil fuel, and a major contributor to the international seafood market, especially, of farmed salmonids (Aandahl and Brækkan, 2023). Moreover, Norway's economic pursuits on the coast are steadily increasing due to, for instance, ambitious plans for the aquaculture sector (Norwegian Ministry of Trade, Industry and Fisheries, 2021) and offshore wind production (Norwegian Ministry of Petroleum and Energy, 2021), and the increasing number of international tourists (Statistics Norway). The complexity and extent of human activities potentially imposes a variety of threats on the Norwegian coastal ecosystem, but also contributes to important services like food and energy production, employment, and economic value creation.

Risk assessments can be a useful starting point for screening, assessing, and communicating how human activities impose a risk of harm to the marine environment. Understanding environmental risk and the factors influencing that risk is important not only for managers and policymakers, but also for stakeholders from different value perceptions to achieve risk acknowledgement and to help existing and emerging activities improve sustainability. Risk assessments are already used as tools for managing different sectors operating in the marine environment. Management of the Norwegian aquaculture sector, for instance, has been founded on annual risk assessments carried out since 2011 (Andersen et al., 2022; Taranger et al., 2015). This provides valuable information for managing the rapid growth of this sector in coastal Norway, but cannot provide decision-makers with the holistic perspective necessary to manage cumulative risk from aquaculture together with other sectors operating in the same environment. Over the past decade or so, however, there has been a development in methods for evaluating ecosystem risk in a cumulative impacts perspective, where all sectors and their associated pressures are assessed in a common framework (e.g. Halpern et al., 2008; Hammar et al., 2020; Holsman et al., 2017; Knights et al., 2015; Pedreschi et al., 2019). These provide a guide for management to identify risks and prioritize measures across a range of sectors (Holsman et al., 2017; Levin et al., 2014). Similar to the risk assessment for the Norwegian aquaculture sector, the aim is not to estimate and quantify the true risk (e.g., probability × consequence) of environmental harm, which in most cases would be an impossible task due to lack of monitoring. Rather, the focus is on establishing a common ground for risk understanding and acknowledgement, to enable effective discussions across a range of stakeholders and decision-makers (Andersen et al., 2022; Knights et al., 2015).

Here, we present the first cumulative risk assessment for Norwegian coastal and adjacent shelf waters, evaluating the potential ecosystem impacts from a wide range (15 in total) of marine and land-based sectors. We target four coastal regions with contrasting characteristics in current human activity and utilize a linkage-framework for mapping the associations between sectors which through their activities are drivers of pressures that may negatively affect one or a range of ecosystem components (Knights et al., 2013; Piet et al., 2017). This creates a conceptual model of multiple cause-effect chains which in the following are scored semi-quantitatively using an exposure-effect approach, under the assumption that the risk of negative impact on the ecosystem increases with exposure to a pressure, and by the severity of the interaction (Piet et al., 2015). Exposure-effect approaches have been suggested to be more suitable than the traditional likelihood-consequence approach for assessing risk from activities already present in the environment (Smith et al., 2007). Albeit a semi-quantitative scoring approach, these types of assessments rely to a large degree on qualitative expert judgements based on varying, but often low, background information (Robinson et al., 2014). Hence, an important part of the assessment is to evaluate the degree of confidence for the judgements made. This may provide additional useful information for managers in prioritizing knowledge needs on potentially high-risk impacts and highlight important knowledge gaps for new scientific endeavors.

With this consolidation of the knowledge of potential human impacts on the coastal regions of Norway, our objectives are multifold. First, we want to evaluate regional differences in cumulative impact risk and sectors' contributions to risk. Following, we evaluate the degree to which individual pressures impose a risk of negative impact across the ecosystem, and detail how this risk is related to individual ecosystem components. We discuss our results in light of recent trends in anthropogenic marine pressures and make suggestions for potential new developments which can enhance the utilization of these types of assessments across multiple stakeholder and managerial levels.

2. Material and methods

2.1. Spatial scale of the assessment

Human activities along the Norwegian coast vary extensively in type and extent from south to north. We based our analyses on a subdivision of the coast into 13 regions with borders reflecting areas of reduced physical connectivity based on dispersal modelling (Fig. 1). These were originally established as a means of regulating aquaculture production aiming at limiting the spread of the parasite salmon lice (*Lepeophtheirus salmonis*) between the regions (Ådlandsvik, 2015). Seawards, the boarders extend 20–30 nautical miles from the baseline, thus covering the adjacent shelf and capturing the Norwegian Coastal Current (NCC) which to a large degree determines the conditions in coastal waters (Sætre et al., 2007). Recently, it has been decided to move the seaward borders of the aquaculture production zones closer to the baseline *sensu* Ådlandsvik (2022). However, we regard the original zoning as more relevant for a coastal ecosystem risk assessment to capture activities occurring at the shelf and within the NCC, which host important ecological processes (Sætre et al., 2007). For instance, the coastal zone and adjacent shelf serves as spawning areas for migratory fish stocks like capelin (*Mallotus villosus*), herring (*Clupea harengus*) and cod (*Gadus morhua*), and spawning migrations into the coast represent a massive transport of energy from ocean to coast supporting more resident, coastal species like the lobster *Homarus gammarus* (Sætre et al., 2007; Varpe et al., 2005).

Our assessment targets four of the 13 coastal regions (regions 3, 4, 9 and 12, highlighted in Fig. 1), which are regions with contrasting characteristics. Regions 3 and 4 cover western Norway stretching from Karmøy (59.2°N) to Stad (62.5°N) and are expected to have high anthropogenic activity and presumed impact. On the border between these regions, we find the second most populated city in Norway, Bergen, with one of the country's major port facilities. Western Norway harbors intense ship traffic, serving as a major junction point for the oil and gas industry in the North Sea and hosting a large proportion (over 65 %) of all cruise ship arrivals to the country (Dybedal, 2018). Several fjords in this region have been characterized as contaminated, in part attributed to historical discharges from land-based industries and freshwater runoff from land (e.g. Azad et al., 2021, 2019; Everaert et al., 2017). One of the country's largest mine tailing deposits will also be established in a fjord (Førdefjorden) located in region 4. Furthermore, regions 3 and 4 are associated with extensive aquaculture production comprising 24 % of the biomass of Norwegian farmed fish produced in 2022 (Grefsrud et al., 2023). Both regions are currently "flagged red" in the traffic light system used for managing the aquaculture industry (Vollset et al., 2022), which means that prevailing levels of salmon lice are considered unsustainable, and farmers are required to reduce their current production capacity.

Regions 9 and 12 are situated in the less densely populated northern Norway. Region 9 covers the Lofoten/Vesterålen archipelago and Vestfjorden, approx. 66.9 to 69.7 °N. The region is a popular destination for nature-based tourism, hosting both national and international tourists. The number of overnight stays per year was approximately 500 000 in 2016–2019, however this is not including private accommodation or free-camping and the actual number could be almost double (Kaltenborn et al., 2019; Kristoffersen and Midtgard, 2016). The sea around Lofoten/Vesterålen harbors important spawning and nursery grounds for fish, and the large North-East Arctic cod stock (NEA cod) migrates to the archipelago every winter to spawn. Hence, the area is one of the most

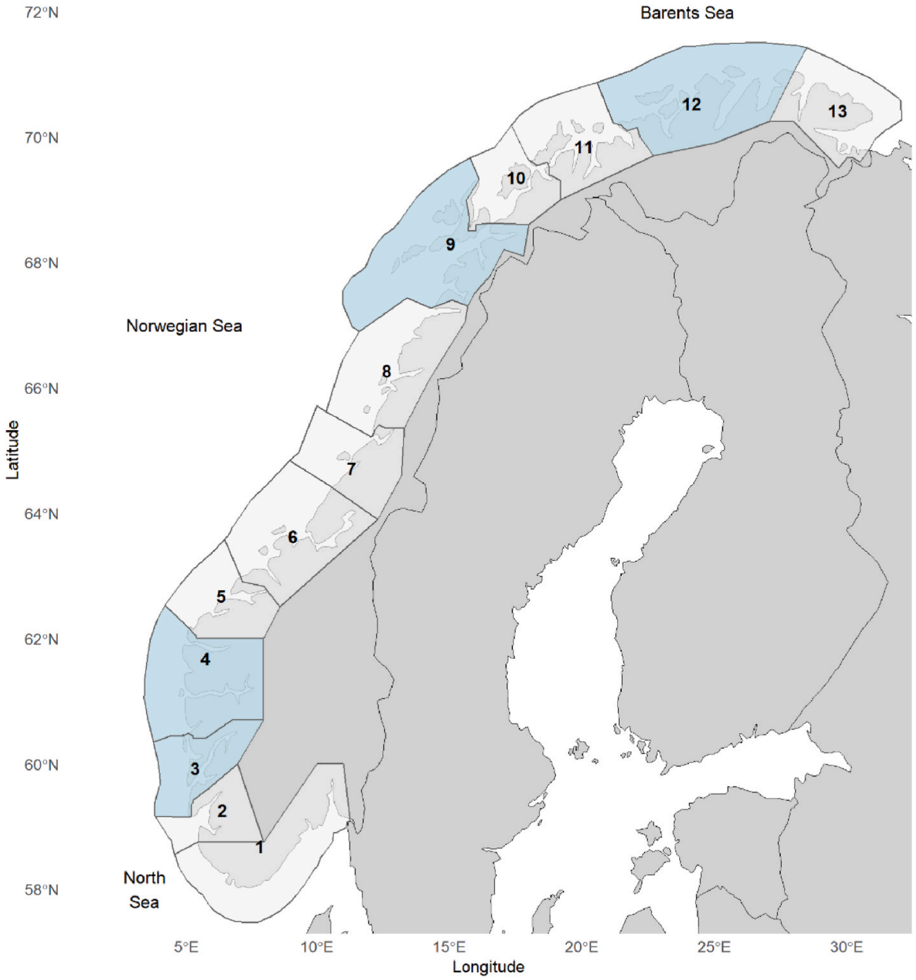

Fig. 1. Subdivision of the Norwegian coast into 13 regions used for managing the national aquaculture industry. For the risk assessment presented here, we focus on the regions highlighted in blue (3, 4, 9 and 12).

important coastal fishing grounds in Norway, and one of the most important cod fishing grounds in the world (Dahle et al., 2018). Region 12 covers the northernmost coast of Norway, including North Cape (71°N) and two large northern fjords (Porsanger and Laksefjorden) with special arctic environmental conditions. The area is sparsely populated with low anthropogenic activity. The fishing industry is important in the region, and there are also several tourist fishing camps operating. Some local fjords are and may in future be more affected by submarine mine tailing deposits.

2.2. Linkage framework: sectors, pressures, and ecosystem components

To assess cumulative impact risk for the coastal ecosystems in the four regions described above, we follow the ODEMM (Options for Delivering Ecosystem-based Marine Management) approach, starting with a linkage framework with the basic elements of sectors (e.g. oil & gas) which, through their activities (e.g. seismic surveys), are drivers for pressures (e.g. underwater noise) that may affect one or multiple ecosystem components (Knights et al., 2013; Robinson et al., 2014). This is associated with the Driver-Pressure-State-Response-Impact (DPSIR) framework (OECD, 1994) focusing on causal links of environmental impacts from human drivers (D, here sectors and their activities) of pressures (P) which are mechanisms of change potentially affecting the state (S) of ecosystem components, habitats or other ecological characteristics (Elliott et al., 2017). Impacts (I) and management responses (R) are not covered in our analysis, we here focus on delineating the complex links between human activities and the coastal, marine ecosystem which is a key first step in efficient marine management (Elliott et al., 2017).

Table 1

Criteria, categories, and values used for scoring the impact chains (sector – pressure – ecosystem component, Fig. 2) in the risk assessment, following Piet et al. (2017). Justifications for the scores are elaborated in Knights et al. (2015) and Piet et al. (2017).

Scoring criterion	Category	Description	Ordinal scores	Weighted scores
Spatial exposure (E_s in Eq. (1))	Site	Ecosystem component is exposed to pressure in >0 % but <5 % of the area assessed	0.33	0.03
	Local	Ecosystem component is exposed to pressure in >5 % but <50 % of the area assessed	0.67	0.37
	Widespread	Ecosystem component is exposed to pressure in 50 % or more of the area assessed	1	1
Temporal exposure (E_t in Eq. (1))	Rare	Ecosystem component is exposed to the pressure up to 1 month per year	0.25	0.08
	Occasional	Exposure up to 4 month per year	0.5	0.33
	Common	Exposure up to 8 month per year	0.75	0.67
	Persistent	Exposure throughout the year	1	1
Degree of impact (*e* in Eq. (1))	Low	Severe effect not expected	0.33	0.01
	Chronic	Pressure may eventually have severe effects if it occurs often enough or at high enough levels	0.67	0.13
	Acute	Immediate and severe effect after a single interaction with the pressure	1	1

A total of 15 sectors were assessed (e.g., marine transportation, fisheries, aquaculture and tourism & recreation), and these were associated with a total of 22 different pressures to the coastal ecosystems (defined in Appendix Table A1). All assessed sectors and associated pressures are detailed in Tables 2 and 3, and the association between sectors and pressures is outlined in Appendix Fig. A1. Data on sector activities were, for many sectors but not all, available through public databases or GIS tools operated by the Norwegian Environment Agency and the Norwegian Fisheries Directorate (Appendix Table A2). We based our analyses on sector activities during the period 2017–2019, which we consider the most recent, representative years given that the normal activities of many sectors were affected by the 2020–2022 pandemic.

We divided the ecosystem into 11 biological ecosystem components, or functional groups, and established impact chains (Knights et al., 2015) that connect sectors to pressures (Appendix Fig. A1), and pressures to the ecosystem components which may be affected (Appendix Fig. A2). Only direct linkages between pressures and ecosystem components were considered in the assessment, not indirect effects e.g., food-web mediated. The linkage framework with its impact chains details potential impacts to the ecosystem from the range of pressures which may or may not be present in the environment. The impact chains (sector – pressure – ecosystem component, Fig. 2) were outlined based on earlier work from European waters (Knights et al., 2015; Robinson et al., 2014) and adapted to Norwegian conditions based on extensive literature review and expert judgement. The impact chains were then scored using an exposure-effect approach to get a weighted impact risk per link established (see below). It should be noted that pressures tied to ship traffic were assessed jointly under marine transportation, also if the traffic was associated with e.g., fishing, oil & gas, cruise tourism or aquaculture operations (see Discussion), in contrast to other applications of the ODEMM framework.

2.3. Weighting of impact chains

Following the ODEMM method, we use and exposure-effect approach to estimate an impact risk (*IR*) for each impact chain (Fig. 2) based on three criteria: the spatial overlap between a sector-pressure combination and an ecosystem component, the frequency to which they co-occur and the generic severity of the interaction or likely degree of impact on the ecosystem component. The product of these three (E_s: exposure in space, E_t: exposure in time, e: effect on ecosystem component, Table 1) constitutes the impact risk, with the underlying assumption that the risk or likelihood of a negative impact increases with exposure to a pressure and by the effect or severity of the interaction (Knights et al., 2015; Piet et al., 2015):

$$IR = E_s \times E_t \times e \tag{Eq. 1}$$

Estimating *IR* for each impact chains provides a weighting of the complex conceptual network from the linkage framework (see above) based on exposure and effect which are factors that contribute to *vulnerability* (De Lange et al., 2010; Stelzenmüller et al., 2018). This allows for an efficient assessment of the sum or mean impact risk by sector and pressure, or to an ecosystem component, and a cumulative total impact risk (i.e., including all sectors, pressures, and ecosystem components) which is comparable between regions.

The distribution of ecosystem components must be taken into consideration when evaluating exposure to pressures from sectors. Given the broad categorization of ecosystem components to levels such as benthic fauna, seabirds, and pelagic fish, most were here assumed to be distributed homogenously within each of the four study regions and present all year round. Exceptions to this were mesopelagic fauna, macroalgae and eelgrass, and anadromous fish. Mesopelagic fauna (e.g. mesopelagic plankton and micronekton) requires deep areas and are hence not present on the continental shelf but were assumed to be distributed in areas (mainly fjords) where the bathymetry is deeper than 200 m. Mesopelagic fauna are considered negligible in the shallow shelf

Table 2
Total number of impact chains (sum across the four regions) weighted and scored for the 15 sectors, and % of impact chains (rounded to nearest integer) assigned to the different ODEMM categories of spatial and temporal exposure, and degree of impact. A description of the categories is presented in Table 1 and elaborated in Knights et al. (2015).

Sector	Total impact chains	Spatial exposure (% of impact chains)			Temporal exposure (% of impact chains)				Degree of impact (% of impact chains)		
		Site	Local	Widespread	Rare	Occasional	Common	Persistent	Low	Chronic	Acute
Marine transportation	191	38	43	18	1	39	60	0	25	67	8
Aquaculture	282	51	48	1	17	4	44	36	35	57	9
Tourism & recreation	217	66	34	0	4	42	53	0	22	64	15
Oil & gas	85	74	26	0	7	49	35	8	19	69	12
Fisheries	245	79	21	0	42	6	51	2	24	62	13
Research	148	89	11	0	59	32	1	7	30	53	16
Agriculture	75	95	5	0	0	49	51	0	27	68	5
Hydropower	76	95	5	0	5	88	3	4	58	37	5
Navigational dredging	172	97	3	0	80	1	20	0	14	72	14
Wastewater treatment	111	97	3	0	0	0	100	0	36	60	4
Landbased industry	75	99	1	0	0	0	100	0	27	68	5
Military	252	99	1	0	23	77	0	0	31	65	5
Coastal infrastructure	227	100	0	0	28	7	51	14	22	66	11
Mining/aggregates	63	100	0	0	5	95	0	0	24	67	10
Telecommunication	104	100	0	0	73	0	0	27	31	62	8

Table 3
Ranking of pressures in terms of their relative importance based on the cumulative (sum) and mean impact risk per pressure in the four regions. Note that the mean impact risk is estimated only accounting for ecosystem components which may be impacted by the pressure (see Appendix Fig. A2). Pressures are sorted based on the ranked cumulative impact risk in region 3, and the top five ranks per region are marked in italics. NP: Nitrogen and Phosphorous. See Appendix Table A1 for definitions of the pressures.

Pressure	Rank cumulative impact risk				Rank mean impact risk			
	Region				Region			
	3	**4**	**9**	**12**	**3**	**4**	**9**	**12**
Contaminants	*1*	*1*	*1*	*1*	*4*	6	6	6
Underwater noise	*2*	*2*	*2*	*2*	*5*	*5*	*5*	*5*
Oil-pollution	*3*	*3*	*4*	*4*	7	7	7	7
Species extraction	*4*	*4*	*3*	*3*	*2*	*2*	*1*	*1*
Abrasion	*5*	*5*	*5*	*5*	*3*	*4*	*3*	*3*
NP enrichment	6	7	6	6	11	11	10	9
Electromagnetic changes	7	6	10	10	8	10	16	15
Siltation	8	8	8	9	14	14	19	17
Translocations/NIS	9	13	13	12	10	13	13	11
Genetic introgression	10	15	14	13	*1*	*3*	*2*	*2*
Parasites	10	9	20	19	*1*	*1*	14	13
Bycatch	11	10	7	7	9	8	*4*	*4*
Barriers	12	12	19	22	6	9	17	22
Light pollution	13	11	11	11	12	12	11	10
Incidental loss	14	16	9	8	16	16	9	8
Litter	15	14	15	14	20	21	21	20
Altered circulation	16	20	16	15	13	19	12	12
Sealing	17	17	17	16	15	15	15	14
Disturbances	18	18	12	18	17	17	8	18
Removal non-living res.	19	19	18	17	18	18	18	16
Salinity changes	20	21	21	20	21	22	22	21
Thermal changes	21	22	22	21	19	20	20	19

Barents Sea and thus were not considered for the assessment of region 12. Macroalgae and eelgrass dominate in shallow coastal waters (Araújo et al., 2016; Duarte, 2022) and therefore were assumed to only be distributed along the coastal zone and in shallow coastal regions down to approximately 20 m depth. Anadromous fish in coastal Norway include Atlantic salmon (*Salmo salar*), brown trout (*Salmo trutta*) and Arctic charr (*Salvelinus alpinus*). Although salmon is only transitorily present in the fjords when migrating to the sea (Bjerck et al., 2021; Jensen et al., 2022; Rikardsen et al., 2021), trout and Arctic charr most often reside inside fjords in the marine phase, where they can be present all year around (Klemetsen et al., 2003). Hence, anadromous fish were evaluated as only present in fjords, throughout the year.

Following Piet et al. (2017) we utilized both weighted and ordinal scorings of E_s, E_t and e (Eq. (1), Table 1), thereby assessing the sensitivity of the results to the choice of scoring method. With ordinal scores there is less numerical distance between the scoring categories, and weighted scores have been suggested as more useful for informing management decisions (Piet et al., 2017). Due to this, we present results using ordinal scores in the supplementary Appendix only.

2.4. *Confidence*

Degree of confidence was evaluated for both exposure and effect (Eq. (1)), on a scale from 1 to 3 with 3 indicating the highest confidence (Appendix Table A3). Confidence for exposure was judged by the degree and quality of information on the distributions in space and time of the assessed pressures and ecosystem components. Data on the spatial and temporal distribution of pressures from specific sectors is generally lacking, so distribution of sector activities in space and time must be used as proxies. Hence, confidence for exposure needs to account for both the quality of information on sector activity, and the expected correlation between the spatial distribution of activities from a sector and a pressure associated with the activity. To give an example; abrasion from the fisheries sector is well known to be highly correlated with bottom trawl activities, while the spatial extent and frequency of littering from fishing activities is not necessarily highly correlated to where fishing occurs. This means that one sector may be associated with varying degrees of confidence for exposure, as some pressures are expected to be more tightly correlated with the spatial operations of the sector than others.

Confidence for effect reflects the knowledge used to score the degree of impact (DoI) a pressure is expected to have on an ecosystem component and was here scored based on the vulnerability assessment with associated confidence scores in Hansen et al. (2022).

3. Results

3.1. *Regional differences in cumulative and mean impact risk*

Overall, we identified a total of 2323 impact chains (Fig. 2, Table 2) which were weighted and scored for the four regions (550–633 impact chains per region). Most sectors had similar numbers of impact chains in

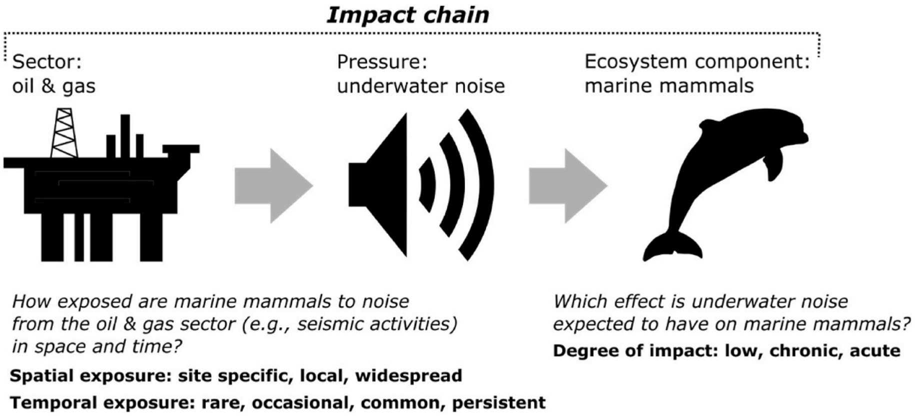

Fig. 2. Example of an impact chain (Knights et al., 2015) connecting pressures from the activities of a sector to an ecosystem component which may be negatively impacted by the pressure. Here, seismic activities from the oil & gas sector generate underwater noise which may have a negative impact on marine mammals. Each impact chain is weighed by how the ecosystem component is exposed spatially and temporally to a pressure from a sector, and by what effect (degree of impact) the pressure is expected to have on the ecosystem component in question. Weighting categories (in bold) are from the ODEMM framework (Knights et al., 2015; Piet et al., 2017) and described in Table 1.

the four regions, meaning that their activities and associated pressures and risk of impact were present in all, though on varying temporal and spatial scales (see below). However, the oil & gas sector had a higher number of impact chains in region 4 where there are several permanent oil and gas installations, and there were no current mining/aggregates activities or active sea deposit permissions in region 3.

The cumulative impact risk varied by a factor of ~1.5 between the regions (Fig. 3a), also reflected in the regional differences in mean impact risk (range 0.0084–0.012). Both the cumulative and mean impact risk was highest in the two southern regions and lower for the northern regions. Four of the 15 sectors made a considerable contribution (>83 %) to the cumulative impact risk in all regions: fisheries, aquaculture, marine transportation, and tourism & recreation. Common for these were that they were associated with pressures with higher average impact risk scores compared to sectors with lower contributions to the cumulative impact risk (Fig. 3b), and a larger proportion of impact chains with high spatial and/or temporal exposure to ecosystem components (Table 2). Marine transportation showed similar impact risk in all four regions (slightly lower in region 12). For fisheries, the sum impact risk was slightly higher for the northern compared to the southern regions, and the mean impact risk per fisheries pressure was also higher in the north (Fig. 3). Lower cumulative impact risks in the northern compared to the southern regions were largely due to lower impact risk scores from tourism & recreation and aquaculture in the north, where these two sectors were considered to have a lower spatiotemporal footprint. Sectors with low contribution to the cumulative impact risk had a large proportion of impact chains with low spatial and/or temporal exposure (Site, Rare, Occasional; Table 2).

3.2. Major risk-contributing pressures

The four regions were relatively similar with regards to the pressures that contributed most to the cumulative impact risk (Fig. 4). Contaminants, underwater noise, oil-pollution, species extraction and abrasion were the top five cumulative pressures in all regions, and among the top ten when judged by the mean impact risk per pressure (Table 3). Multiple sectors added to the impact risk from contaminants, with marine transportation, aquaculture, and tourism & recreation (primarily southern regions) as prominent sources of risk. Land-based polluting sectors (agriculture, coastal infrastructure, land-based industry, and wastewater treatment) had in general a lower contribution to the impact risk from contaminants compared to sectors with marine operations. Marine transportation and tourism & recreation were largely responsible for the impact risk from underwater noise in all regions, while aquaculture was a noteworthy source of noise only in the south, and oil & gas in regions 3 and 12 where the most extensive seismic activities had taken place.

Species extraction was among the top two pressures in all regions when ranked according to the mean impact risk, and the top four judged by the cumulative impact risk. Fisheries was the major sector (>85 %) contributing to risk associated with species extraction, while tourism & recreation, research, and aquaculture had small contributions to this pressure. Fisheries was also the major risk source for abrasion (>70 %), accompanied by small contributions from mainly navigational dredging, tourism & recreation, marine transportation, and research.

Parasites and genetic introgression from aquaculture ranked high (top 3) for mean impact risk in the southernmost regions but had a lower rank in the cumulative impact risk. These pressures were only associated with one of the 11 ecosystem components, the anadromous fish (Appendix Fig. A2), and made a considerable contribution (>20 %) to the cumulative impact risk for this group in the southern regions (Fig. 4) even though they arise from one single sector. However, summarizing across all ecosystem components makes the relative risk contribution from these two pressures smaller, reflected in the lower rank for cumulative impact risk (Table 3).

Contaminants, underwater noise and oil-pollution, on the other hand, were pressures associated with many sectors (Fig. 4) with potential to negatively impact a range of ecosystem components (Fig. 5), which is why they made a large contribution to the cumulative impact risk (Table 3). Thermal changes, salinity changes, altered circulation, removal of non-living resources and sealing (habitat loss) made a negligible contribution to the cumulative impact risk in all regions (Fig. 4, Table 3). These were associated with sectors with low spatial and/or temporal exposure (Table 2, Appendix Fig. A1) which is partly why they scored so low here.

3.3. Ecosystem components at risk

The 11 ecosystem components were associated with between 7 and 15 individual pressures (or 4 to 13 disregarding pressures expected to

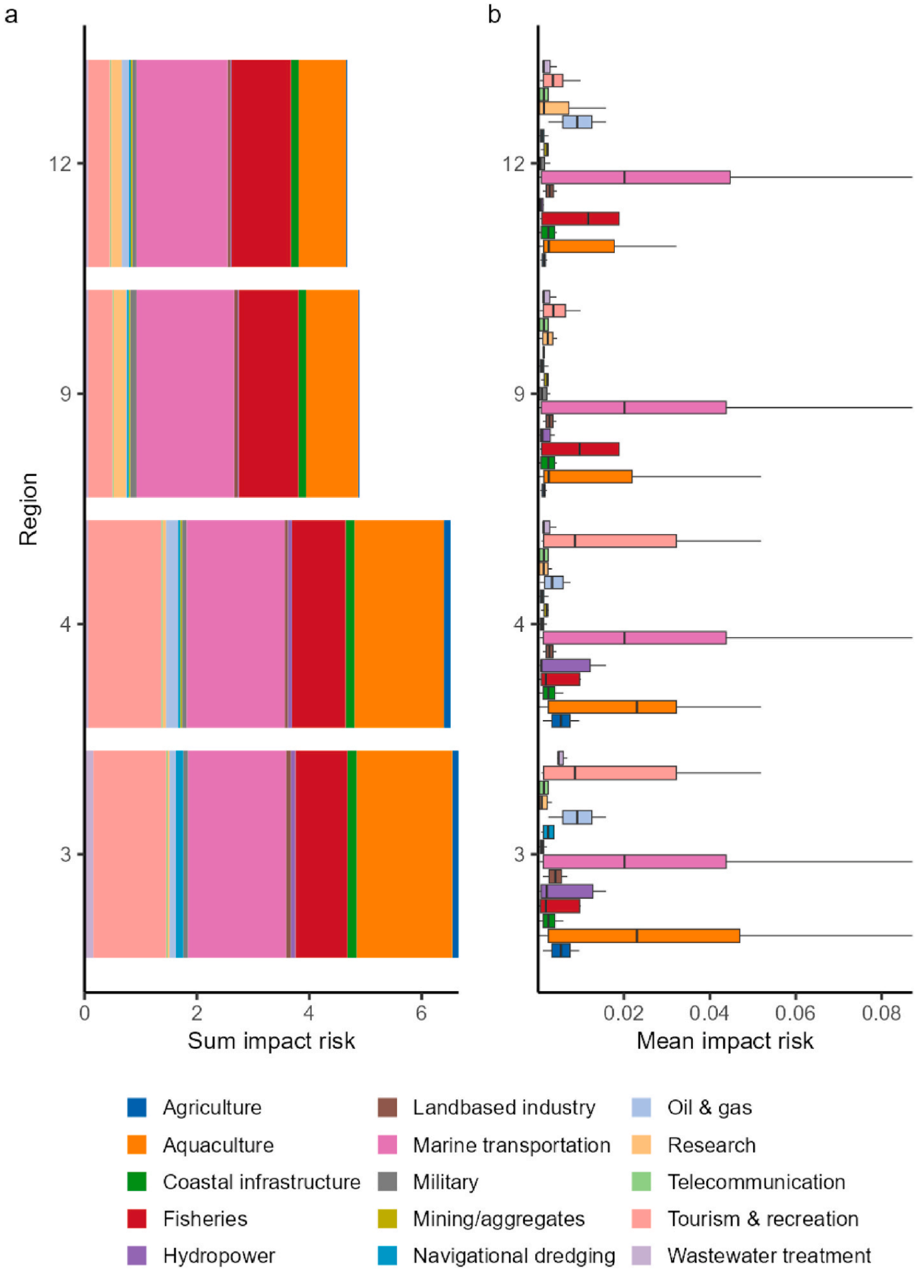

Fig. 3. **a)** Cumulative impact risk by region and sector and **b)** mean impact risk per pressure for the 15 assessed sectors in the four regions. Outliers in **b)** have been omitted to enhance visualization.

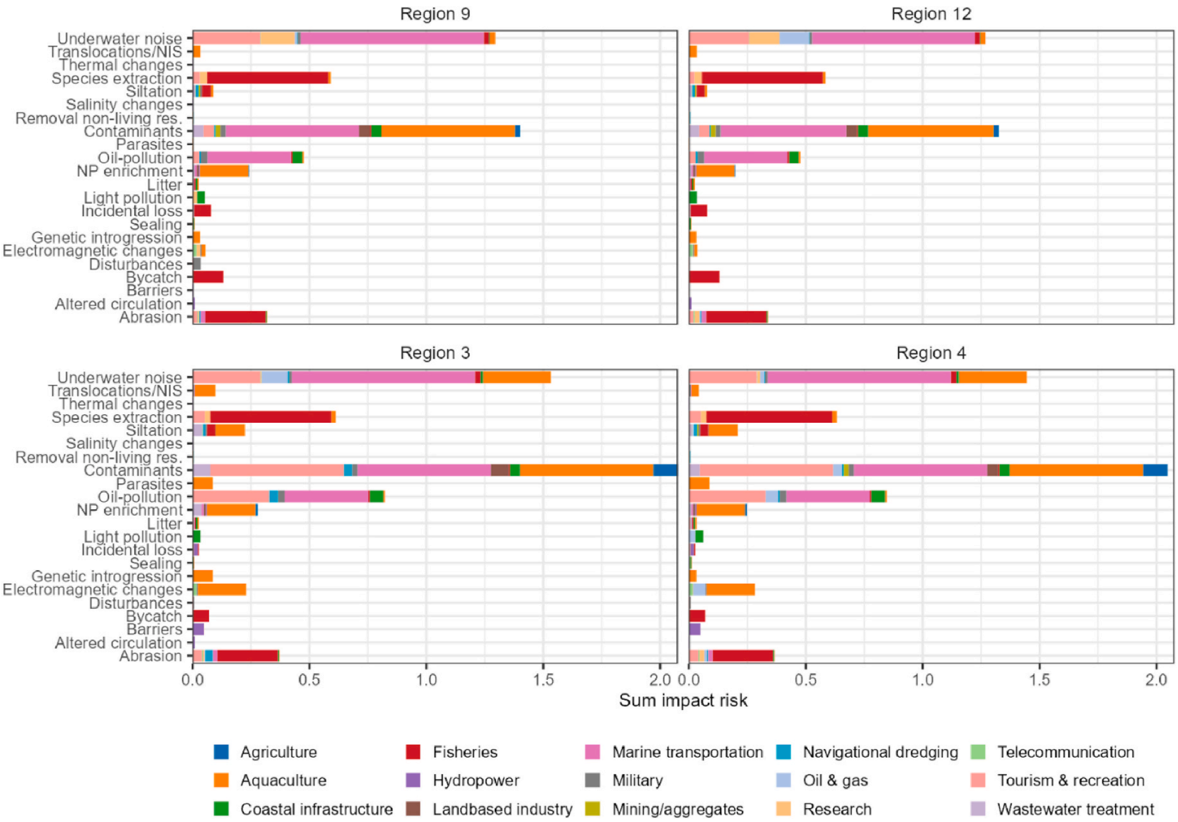

Fig. 4. Cumulative impact risk per pressure in the four regions, colored by the contribution from each sector to the different pressures. NP = Nitrogen and Phosphorous.

have low degree of impact). Mesopelagic fauna were associated with the least number of pressures, while benthic fauna and anadromous fish were associated with the most pressures (Appendix Fig. A2).

Early life-stages of fish (fish ELS), benthic fauna, pelagic and demersal fish scored high for cumulative impact risk in all regions (Fig. 5). Together, these groups comprised 45–50 % of the cumulative impact risk score by region. Anadromous fish also had high impact risk in regions 3 and 4, though lower in the two northern regions. Seabirds had an impact risk similar to that of pelagic fish in the southern regions, but also somewhat lower for the northern ones. In sum, anadromous fish were among the top five ecosystem components at risk in the south, while seabirds were among the top five in the north (see Discussion Fig. 7).

Fish ELS was the ecosystem component associated with the highest risk of negative impact across the four regions, with major risk contributions from contaminants and oil-pollution. Species extraction was the dominant risk-contributing pressure for pelagic and demersal fish, while abrasion gave a high risk to benthic fauna. The dominant risk contributions reflect to a large degree the pressures that are expected to have acute effects on these ecosystem components (Appendix Fig. A2), but not exclusively. Benthic fauna are also expected to be acutely affected by sealing, which had a negligible contribution to benthic fauna risk here due to low scores for exposure. Similarly, altered circulation is expected to acutely affect fish ELS, but they were not considered very exposed to this pressure. Furthermore, pressures considered to give chronic effects also had a noteworthy contribution to risk for the ecosystem components where the potential for exposure was considered high, e.g., underwater noise and contaminants (most ecosystem components), genetic introgression and parasites (anadromous fish).

3.4. *Confidence exposure and impact*

Knowledge gaps emerge when evaluating our confidence in 1) how exposed the ecosystem components are (in space/time) to pressures from different sectors and 2) what effect the pressures are expected to have on the ecosystem components (Fig. 6). Underwater noise stands out as a pressure with low confidence in exposure from many sectors, low confidence in effect for many ecosystem components, and high contribution to the cumulative impact risk. For contaminants and oil-pollution, there was higher confidence in effect on the ecosystem components, but generally low confidence in exposure. Marine transportation and tourism & recreation stood out as sectors with high contribution to cumulative impact risk but associated with low confidence. For aquaculture and fisheries, on the other hand, there was higher confidence in exposure to their main risk-contributing pressures.

4. Discussion

We have presented the first systematic assessment of risk from sectors and associated pressures on the Norwegian coastal ecosystem. Results encapsulate the complex ways in which human activities interact with the coastal marine environment, and how different activities impose risk to various marine biotic groups. We demonstrate that latitudinal differences in the use of ocean space results in regional differences in ecosystem risk, though the dominating pressures and ecosystem components associated with the highest risk of impact remained fairly constant between regions. The impact risk from cumulative human activities was lower in the northern compared to the southern regions, largely due to lower impact risk from aquaculture and tourism & recreation in the north (Fig. 7). Early life stages of fish, benthic fauna, demersal and pelagic fish were amongst the top five ecosystem components at risk in all four regions, and the difference between the

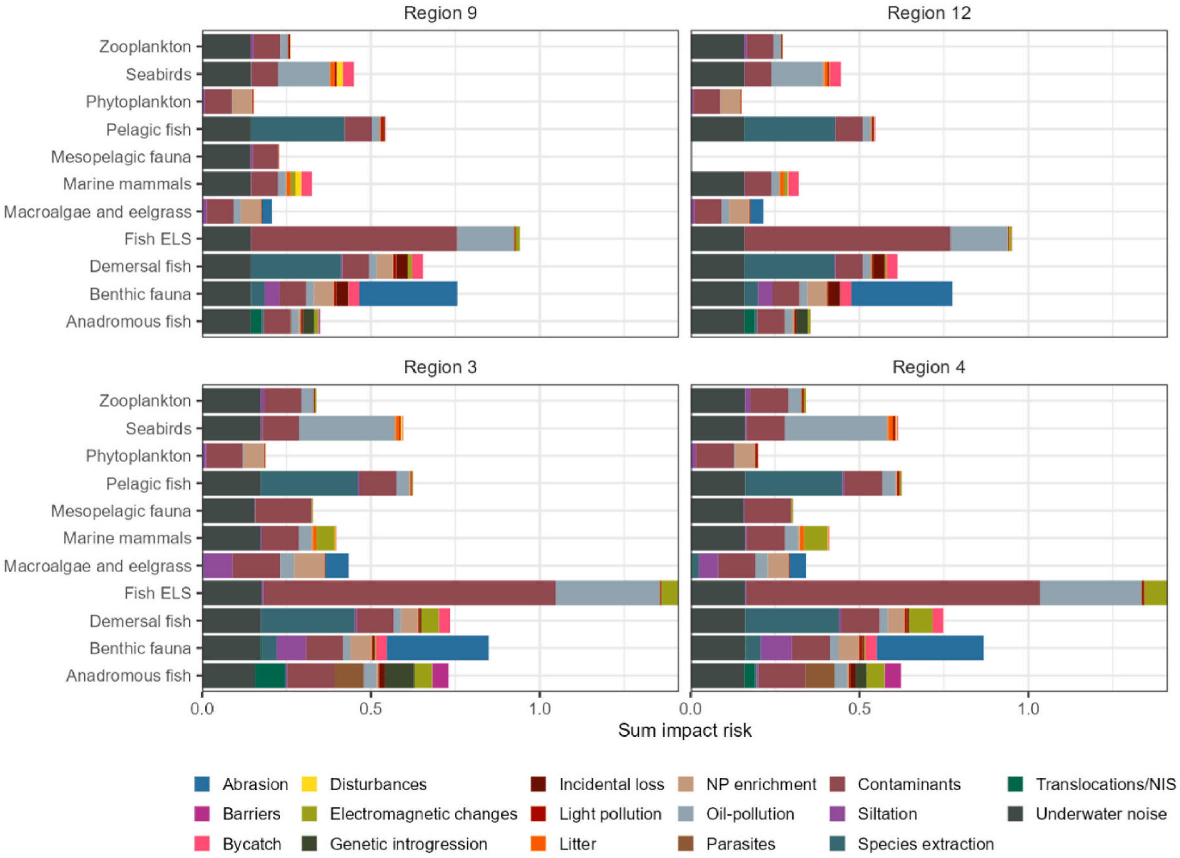

Fig. 5. Cumulative impact risk per ecosystem component in the four regions, colored by the contribution from the different pressures. Five pressures with low contribution to cumulative impact risk (thermal changes, salinity changes, removal of non-living resources, sealing and altered circulation; Fig. 4) have been omitted to enhance the visualization. Fish ELS = early life stages of fish, NP = Nitrogen and Phosphorous. Note that mesopelagic fauna are not considered to be present in Region 12.

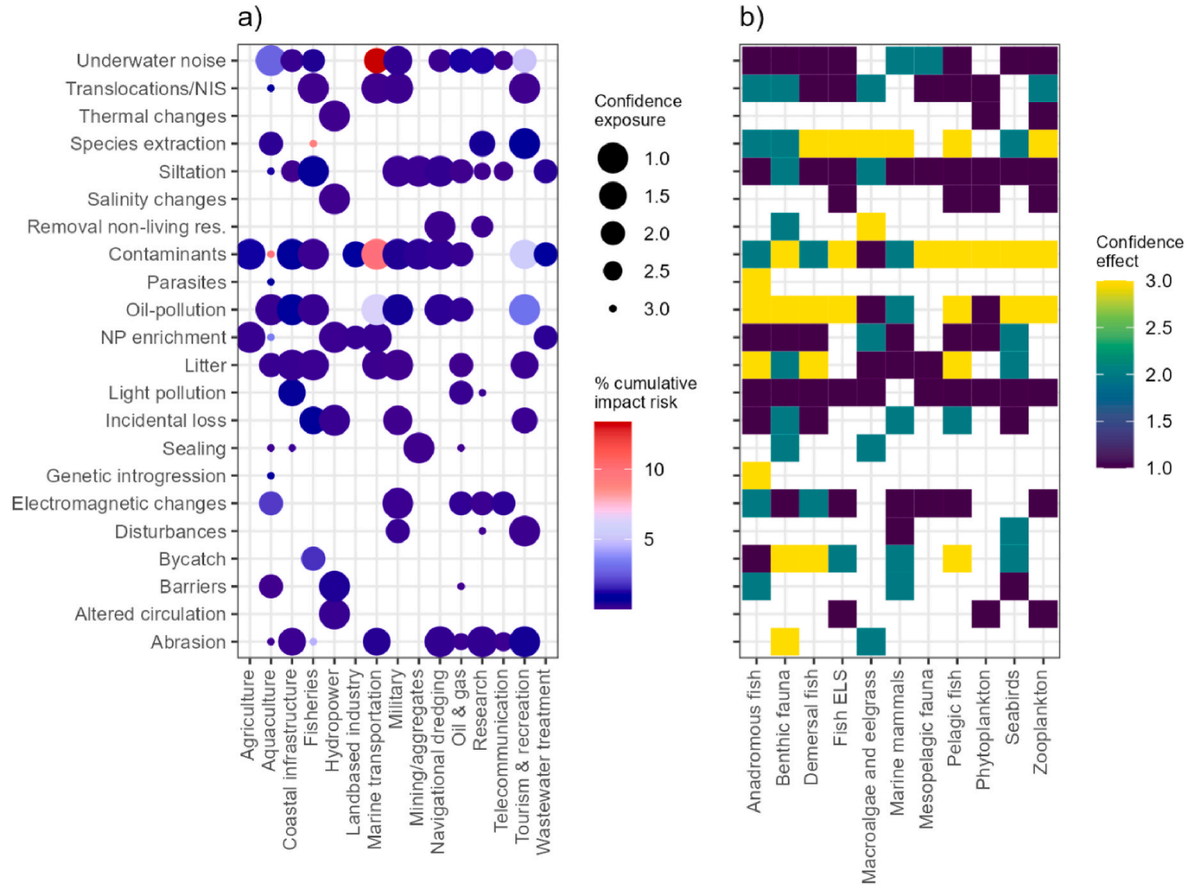

Fig. 6. **a)** Mean confidence exposure to sector-pressure combinations, confidence has been scored between 1 (low) and 3 (high) (Appendix Table A3). Note that large circles indicate low and small circles indicate high confidence. Circles are color coded by the relative contribution of the sector-pressure combination to the cumulative impact risk score (sum across all 4 regions). **b)** Confidence for which effect the pressures are expected to have on the ecosystem components, scored (1–3) for individual pressures regardless of sector, and based on Hansen et al. (2022).

northern compared to the southern regions was that seabirds were among the top five in the northern ones, while anadromous fish were among top five in the southern regions where the exposure to risk from aquaculture (salmon farming) is higher (Fig. 7).

Examining the cumulative impact risk by pressure and ecosystem component enables a more detailed insight into why some sectors stand out in their contribution to ecosystem risk. Major pressures from marine transportation and tourism & recreation were underwater noise, contaminants and oil-pollution, which are pressures that potentially affect many ecosystem components with an expected “chronic” or “acute” degree of impact. For fisheries, the major pressures were species extraction and abrasion, which impacts fewer ecosystem components, but the effect is expected to be acute. Aquaculture associated pressures represent a more complex interaction with the coastal ecosystem. Contaminants and underwater noise from aquaculture may affect a wide range of ecosystem components while pressures like salmon lice and genetic introgression are only relevant for one group (anadromous fish) for which the impact risk is relatively high.

4.1. Management relevance

A key strength of the widely established ODEMM framework utilized here is the semi-quantitative risk scoring which enables comparisons between risk-contributing sectors and between regions. The approach was identified as a highly effective method due to high flexibility, adaptability, and ease of use when reviewed alongside eleven other ecosystem risk assessment methodologies during a recent ICES workshop (Pedreschi et al., 2023). It allows a more holistic context for advice, and focusing on pressures arising from regular activities highlights the “day to day” pressures on the coastal environment which are often overlooked in favor of wildcards or high-risk scenarios such as oil spills. Furthermore, an important added value to management is the synthetization of knowledge from a wide range of grey and peer-reviewed literature. Methodological decisions will impact the outcome of how sectors and pressures contribute to the cumulative impact risk (see below), but the mere process of systematically connecting sectors (or activities) with pressures and the evaluation of how ecosystem components may be affected by these (e.g., Appendix Figs. A1 and A2) brings forward important information from the scientific community to decision-makers (Korpinen and Andersen 2016). This step alone may facilitate a common ground for risk understanding and acceptance and should be readily available and open for discussions with management, policymakers, and other stakeholders.

Norway, as many other nations, are aiming to achieve an ecosystem approach to ocean management in response to international (e.g., The Convention of Biological Diversity) and national commitments. The national Nature Diversity Act states that any impact on the ecosystem must be evaluated in a cumulative impact perspective (§ 10), and the primary objective of the national cross sector ocean management plans is to balance value creation, sector activities and sustainable impacts (Faglig forum for norske havområder, 2022). IEA frameworks, including the ODEMM approach, represent the best available means to organize knowledge and expert judgements on the extent of human pressures and their interactions within a complex ecosystem context, thus supporting management decisions based on an integrated ecosystem perspective (Robinson and Culhane, 2020). While cumulative impact assessments

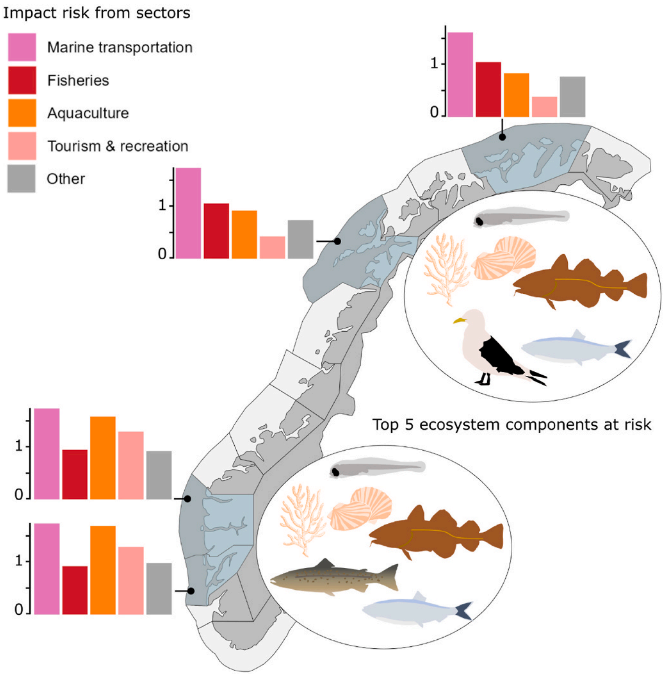

Fig. 7. Sum impact risk by sectors, and top 5 ecosystem components at risk in the four regions assessed. Marine transportation, fisheries, aquaculture, and tourism & recreation are the main risk-contributing sectors in all regions. The impact risk from aquaculture and tourism & recreation varies more from south to north compared to that of marine transportation and fisheries. Early life-stages of fish, benthic fauna, demersal fish, and pelagic fish are among the top five ecosystem components at risk in all regions. Seabirds are among the top five in the northern regions and anadromous fish in the southern ones.

can identify where management actions are most necessary to reduce current risks to the coastal ecosystem, it can also be used to evaluate scenarios for future development (e.g. Hammar et al., 2020). Projecting pathways for future coastal use including an evaluation of change to ecosystem risk will better integrate environmental impacts into strategic planning, which is urgently needed in the era of the “blue acceleration” (Jouffray et al., 2020).

4.2. *Identifying knowledge gaps*

Evaluation of confidence is key for the usefulness and validity of any risk assessment presented to stakeholders (Andersen et al., 2022) and may bring forward important knowledge gaps (Robinson et al., 2014). In our assessment, underwater noise stood out as a pressure with the potential to negatively affect a range of ecosystem components, but where the knowledge on both exposure and effect was considered as low. Marine transportation was the dominant contributor to noise across regions, due to the wide-ranging and frequent presence of this sector in the coastal/shelf environment. Global trends in noise emissions from shipping suggest a doubling of noise every 11.5 years on average, and at a faster rate (5–7 years) in the Norwegian Sea and in the Arctic (Jalkanen et al., 2022). Currently, there is strong evidence that anthropogenic noise is a stressor for marine mammals, but less is known about how noise affects other ecosystem components that use sound for communication and orientation (Duarte et al., 2021), and how behavioral effects on individuals may translate into population-level consequences. Recent studies suggest that ship noise emissions can negatively affect zooplankton feeding rates (Kühn et al., 2023) which could ultimately alter how energy from primary production is transferred up the coastal food web. Given the range of ecosystem components that might respond negatively to noise and the multitude of sectors in the coastal zone contributing to noise, new knowledge in this field should be given priority.

Release of contaminants was also identified as a pressure with large contribution to the cumulative risk of negative impact in all four regions, to a large degree associated with marine transportation, aquaculture, and tourism & recreation. Chemical pressures associated with our definition of contaminants has given a high contribution to cumulative impact risk assessed for biota in other regions as well (e.g. Borgwardt et al., 2019; Piet et al., 2023). In our study, contaminants is a relatively wide term (definition in Appendix Table A1) and the different sectors may be associated with different types of substances. Typical contaminants associated with the aquaculture sector are chemicals used to combat salmon lice (de-licing agents), pesticides and other residues of substances from plant-based feed, and copper (Cu) on the net pens used for antifouling purposes (e.g. Evenseth et al., 2023 and references therein). Confidence in exposure to contaminants from aquaculture was medium to high based on the study of waste spreading and impacts from environmental monitoring (e.g. Evenseth et al., 2023; Grefsrud et al., 2023). However, less focus has been given to the release of contaminants from tourism & recreation (primarily leisure boats) and marine transportation in Norway hence the confidence in exposure to contaminants from these sectors was evaluated as low. Studies from the adjacent Baltic Sea show that both commercial shipping and leisure boats are significant sources of marine contaminants e.g. through to release of copper and zink (Zi) from antifouling paint on the vessels (Johansson et al., 2020; Ytreberg et al., 2022), which could certainly also be the case for Norwegian coastal waters and deserves attention. Our assessment can be considered an initial risk-screening, prioritization and evaluation which is a key step of a cumulative effects assessment (Judd et al., 2015), here delineating the range of sources of contaminants in coastal and shelf waters and which groups in the ecosystem that could be vulnerable to this pressure. We show that contaminants constitute a high ecosystem risk since most ecosystem components are sensitive to contaminants, in particular the early life-stages of fish for which this is an acute pressure (Fig. 5, Appendix Fig. A2). Nevertheless, more in-depth studies are necessary to better link the type and amounts of contaminants released from the different sectors, individually and combined, to the ecosystem components sensitive to these.

4.3. *Limitations*

A challenge of all risk assessment frameworks is to provide knowledge at relevant spatial, temporal and organizational scales for management while also maintaining relevance on ecological scales. The ODEMM framework is relatively flexible with regards to the spatial and organizational scales that it can address, and thus constitutes a powerful decision-making support tool. It is, however, conceptually prone to inconsistencies and methodological bias. Despite the wide acceptance of ODEMM as an effective operation tool for IEAs, the method requires a lot of expert judgement and hence the need for involvement of many different expert groups with knowledge on specific sectors, pressures, or ecosystem components. It may therefore be challenging to ensure that scoring of impact chains is consistent across expert groups. In our case, much time was spent on reviewing individual scorings across sectors and regions to ensure consistency, which certainly made the assessment time-consuming as cautioned by Robinson et al. (2014). In addition, the method includes only spatial and temporal extent of sectors and pressures which may not always be a good indication of intensity of activities, also noted by Knights et al. (2015). For example, the intensity of ship traffic is higher in the southern compared to the northern areas of the Norwegian coast, but this is not well reflected in our results.

Earlier work has demonstrated how the methodological design of the linkage framework (e.g., the choice and definition of risk factors) and the calculation and aggregation of risk will impact the identification and prioritization of “hazards” (Piet et al., 2017). Here, we aggregated risk factors by sectors aligning with the sector-based structure of Norwegian ocean management. Hence, pressures from vessel traffic were evaluated jointly under marine transportation, which is managed by the Norwegian Maritime Directorate, although one can also argue that vessel traffic and associated pressures are inevitably interlinked with both fishing, aquaculture and oil & gas activities. These adaptations differ from other applications of the ODEMM framework (e.g. Knights et al., 2015) and were made based on discussions with the Management group, an advisory body for the Norwegian cross-sector ocean management plans. Their concern was that it was difficult to relate to an assessment where the risk from a sector did not reflect the pressures managed by the sector authorities. Though these adaptations make our assessment less comparable with other international ODEMM applications, we believe they are necessary to enhance relevance and uptake of the analyses in national decision- and policymaking. We furthermore evaluated how our results would change by the choice of scoring method (ordinal *versus* weighted scores Table 1, Piet et al., 2017). With ordinal scores, the risk assessment becomes more homogenous with less distance between risk contributing sectors (Appendix Fig. A3). Contaminants and underwater noise remain the top two risk-contributing pressures, but the overall picture changes e.g. with pressures that had a low risk-contribution with weighted scores (e.g. nitrogen and phosphorous enrichment, litter, and electromagnetic changes) becoming more relevant for the cumulative risk picture (Appendix Fig. A4). Furthermore, several pressures with a chronic degree of impact bypasses acute pressures in the risk-contribution to ecosystem components (Appendix Fig. A5). We suggest that both results (weighted and ordinal scoring of impact chains) are informative to management and should be presented for transparency and insight into how methodological decisions affect the outcome of the assessment.

One potentially major bias is the definition of ecosystem boundaries or the spatial scale of the assessment, which to a large degree will impact the outcome of the risk analysis and its relevance for management. This methodological aspect has, to our knowledge, not been addressed in previous ODEMM applications. The evaluation of spatial extent of pressures (widespread, local or site specific, Table 1) inevitably depends on the size of the region in focus. Pressures are less likely to be scored with a widespread overlap e.g. in a large marine ecosystem than in a smaller coastal region, leading to fewer sectors emerging as problematic on larger scales (e.g. Pedreschi et al., 2019). Our assessment focused on smaller regions than Pedreschi et al. (2019), but we still recognize that nearshore pressures which may be important for local management of fjords and coastal waters (e.g. mining deposits, wastewater treatment, or freshwater regulation for hydropower production) make a small contribution to the cumulative impact risk in our assessment. Due to this scale-dependency, our results will presumably have lower value in decision support for a local compared to a national manager, which is also a challenge for cumulative impact assessments that are spatially resolved on global or regional scales (Korpinen et al., 2021). Including spatial resolution facilitates use of the assessment in marine spatial planning (Hammar et al., 2020), though currently these are often also scale dependent with the cumulative impact evaluated on a relative scale (i.e., in relation to the maximum estimate for the region assessed, see review by Korpinen and Andersen, 2016). An important future step will in our view be to develop spatially resolved risk assessment methods which are scale independent, so that the same assessment can support management decisions at both local, regional, and national levels, and facilitate meaningful international comparisons.

4.4. *From cumulative risk to sustainability*

What is sustainable use of ocean space and resources? Cumulative risk assessments enable a more holistic approach to marine management but will not provide an answer to whether the current use of the ocean is sustainable or not. Our assessment revealed a latitudinal difference in ecosystem risk from cumulative activities, but a higher risk of negative impacts does not mean that the cumulative activities in the southern regions are unsustainable today. In a recent publication on sustainable use of the ocean, Bailey and Hopkins (2023) argue that "*assessments of sustainability are judgements about the future*". By framing the concept of sustainability according to the original definition from the World Commission on Environment and Development (the "Brundtland report", Anonymous, 1987), they demonstrate that assessment of sustainability should relate to intergenerational equity, i.e. that the current use of the ocean must not hamper the potential use for future generations – which may have different needs than we have today. Hence, we can accept that current use alters or even reduces the state and functioning ecosystems, but only if the impacts are reversible within societally acceptable timeframes, and the recovery potential for the ecosystem is not harmed (Bailey and Hopkins, 2023). The concept of reversibility of impacts can to some degree be related to the assessment of persistence of pressures from the ODEMM approach (Knights et al., 2015). They define persistence as the time-period (low 0–2 years, medium 2–10 years, high 10–100 years, continuous >100 years) over which a pressure will continue to impact the environment after the activity introducing the pressure has ceased. Following, high-risk pressures with high to continuous persistence (e.g. contaminants in our assessment) should be given higher management priority considering sustainability, compared to high-risk pressures with lower persistence (e.g. underwater noise).

The ecosystem's recovery potential will, however, also be of relevance when evaluating the reversibility of our actions hence sustainability. In a cumulative impact perspective, this is perhaps the most challenging but also most critical aspect to evaluate. How much pressure can we impose on the coastal marine environment without harming the ecosystem's capacity to return to its natural state? The ODEMM approach suggests an evaluation of resilience or recovery potential for individual ecosystem components (Knights et al., 2015), but here the method falls short in that it does not consider *indirect* effects or ecosystem *dependencies*. Ecosystem resilience concerns the perseverance of relationships within a system (Holling, 1973) hence cannot be limited to individual groups or habitats. To evaluate an ecosystem's recovery potential from cumulative pressures would require cessation of all activities in a region, which might seem unrealistic. Recent international agreements might, however, provide a window of opportunity here. Bailey and Hopkins (2023) propose to use Marine Protected Areas (MPAs) as a tool for evaluating ecosystem recovery potential, and with the Kunming-Montreal biodiversity agreement (Stephens, 2023), nations have agreed to conserve and protect 30 % of coastal and marine regions by 2030. This constitutes a historic opportunity to select MPAs representative for wider coastal regions, for a general evaluation of ecosystem recoverability and to test how sustainable our cumulative use of coastal space and resources really is.

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CRediT authorship contribution statement

Johanna M. Aarflot: Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Conceptualization. **Vilde R. Bjørdal:** Writing – review & editing, Investigation. **Katherine M. Dunlop:** Writing – review & editing, Methodology, Investigation. **Marina Espinasse:** Writing – review & editing, Methodology, Investigation. **Bérengère Husson:** Writing – review & editing, Methodology, Investigation. **Ulf Lindstrøm:** Writing – review & editing, Methodology, Investigation. **Felicia Keulder-Stenevik:** Writing – review & editing, Methodology, Investigation. **Kotaro Ono:** Writing – review & editing, Methodology, Investigation. **Anna Siwertsson:** Writing – review & editing, Methodology, Investigation. **Mette Skern-Mauritzen:** Writing – review & editing, Methodology, Conceptualization.

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

The scoring of spatial and temporal exposure of ecosystem components to pressures from sectors in the four regions are made available as Supplementary material to this article.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ocecoaman.2024.107299.

Appendix

Table A1
Definition of pressures, and association with pressures from ODEMM (Robinson et al., 2014).

Pressure	Description	ODEMM pressure
Abrasion	Physical interaction of human activities with the seafloor and with seabed fauna/flora causing physical damage and/or mortality (e.g. from trawling or anchoring).	Abrasion
Altered circulation	Changes in surface currents and circulation regimes arising from regulation of natural freshwater runoff (hydropower production).	Water flow rate changes (but not associated with hydropower production)
Barriers	Preventing the natural movement of motile marine fauna along a key route of travel (e.g. migration or foraging routes) due to barrages, causeways, wind turbines, freshwater regulation/hydropower turbines and other man-made installations and structures.	Barrier to species movements
Bycatch	Unwanted/illegal catch (that ends up in the net/on board)	Not a pressure in ODEMM
Disturbances	Presence of humans negatively affecting wild species (e.g. disturbance of mating, reduced protection of offspring). Not including human presence on vessels (covered by other pressures).	Not a pressure in ODEMM
Electromagnetic changes	Change in the amount and/or distribution and/or periodicity of electromagnetic energy in a marine area (e.g. from electrical sources such as underwater cables).	Electromagnetic changes
Genetic introgression	Permanent changes/introgression in the genetic characteristics of a species because of human activities. Here associated with salmon aquaculture and escapees, which through interbreeding with wild salmonids threaten the genetic integrity of wild salmon populations.	Not a pressure in ODEMM
Incidental loss	Unintentional collateral damage pertaining to species, e.g. due to collisions with ships or entanglement in lost fishing gear (ghost fishing).	Death or injury by collision (did not include entanglement in fishing gear)
Light pollution	Artificial light from permanent installations (e.g. coastal infrastructure, aquaculture sites, oil & gas platforms)	Not a pressure in ODEMM
Litter	Litter entering the marine environment (e.g. metal, glass, rubber, wood, cloth, and plastics). Not including loss of fishing gear (considered in "incidental loss").	Marine litter
NP enrichment	Organic enrichment e.g. from industrial and sewage effluent input and/or fertilizers, aquaculture feed and other nitrogen and phosphorous rich substances entered into rivers and coastal areas.	Nitrogen and Phosphorus enrichment Input of organic matter
Oil-pollution	Introduction of hydrocarbons into marine waters, e.g. from produced water (oil platforms) or operational discharges and leakages from shipping and leisure boats.	Included in introduction of non-synthetic compounds (hydrocarbons and heavy metals)
Parasites	Elevated densities of parasites due to human activities. Here associated with aquaculture production generating elevated densities of salmon lice, which infect and threaten wild populations of anadromous fish.	Not a pressure in ODEMM
Contaminants	Introduction of heavy metals and synthetic (man-made) compounds, e.g. pesticides, other persistent organic pollutants, antifoulants, and pharmaceuticals, into marine waters.	Introduction of synthetic compounds Introduction of non-synthetic compounds
Removal of non-living resources	Coastal sand and gravel (aggregates) extraction, or removal of surface substrates for exploration of seabed and subsoil (e.g. deep-sea mining).	Selective extraction of non-living resources
Salinity changes	Change in salinity (average, range, variability) e.g. due to regulation of natural runoff for hydropower production	Salinity change
Sealing	Physical loss of habitat from sealing of the seafloor by permanent construction	Sealing
Siltation	Change in the concentration and/or distribution of suspended sediments in the water column from wastewater effluents, dredging, trawling, etc. Also including the covering of habitat surface with material falling to the sea floor from aquaculture waste, around trawling gear etc.	Changes in siltation Smothering
Species extraction	Targeted species extraction	Selective extraction of species (included bycatch)
Thermal change	Change in temperature (average, range, variability) e.g. due to regulation of natural runoff for hydropower production	Thermal change
Translocations and introduction of non-indigenous species (NIS)	Introduction of non-indigenous species and translocations of species by the activities of a particular sector (e.g. through biofouling on ships or use of "cleaner fish" in aquaculture)	Translocations and introduction of non-indigenous species
Underwater noise	Underwater sound from anthropogenic sources (e.g. shipping, fishing, geological investigations, harbor operations).	Underwater noise

Table A2
Data sources used for assessing sector activities.

Sector	Data type	Source	Comment
Agriculture	No data available		
Aquaculture	Aquaculture risk assessment report	https://www.hi.no/hi/nettrapporter/rapport-fra-havforskningen-2023-6	Region-based, qualitative assessment on the severity and spatial extent of some pressures from the aquaculture industry. Currently main focus is on pressures on wild salmonoids and benthic habitats.
	Site locations	https://www.fiskeridir.no/Akvakultur/Registre-og-skjema/akvakulturregisteret	
Coastal infrastructure	Coastal area occupied by infrastructure	https://kart.ssb.no	
Fisheries	Fishing activity by gear use	https://portal.fiskeridir.no/portal/apps/webappviewer/index.html?id=ea6c536f760548fe9f56e6edcc4825d8	
	Lost fishing gear	https://portal.fiskeridir.no/portal/apps/webappviewer/index.html?id=ea6c536f760548fe9f56e6edcc4825d8	Only reported losses
Hydropower	Plant locations	https://atlas.nve.no	
Land-based industry	Plant locations	https://vannmiljo.miljodirektoratet.no/	
Marine transportation	Vessel traffic	https://kart.barentswatch.no/https://kart.kystverket.no/share/9220e0e277e4	By vessel category
Military	Vessel traffic	https://kart.barentswatch.no/	Police- and military vessels
	Shooting/training fields	https://kart.barentswatch.no/https://www.regjeringen.no/contentassets/b069fb1dbe854837a6c268c43f4ff174/horingsnotat-forskrift-om-skyte-og-ovingsfelt-i-sjo.pdf	
Mining/aggregates	Mine tailing deposit sites	Terje van der Meeren (IMR), pers.comm.	
Navigational dredging	Location of permissions allocated in the Norwegian Pollution Database	State Administrator	Data on request. No information on spatial extent or frequency of dredging.
Oil and gas	Platforms	https://kart.barentswatch.no/	
	Pipelines	https://kart.barentswatch.no/	
	Seismic surveys	https://www.npd.no/en/about-us/open-data/	Polygons of completed surveys
	EMF surveys	https://www.npd.no/en/about-us/open-data/	Polygons of completed surveys
	Pollution/emissions	https://www.norskeutslipp.no/no/Petroleumsvirksomhet-til-havs/?SectorID=700	Absolute amounts (not area of influence)
Research	Marine geological survey data	Norges geologiske undersøkelse - NGU https://geo.ngu.no/kart/marin_mobil/https://geo.ngu.no/kart/geofysikk_mobil	Data on request. Sediment sampling, seismic survey physical and GIS data from geological surveys
	Ecological research survey data	http://metadata.nmdc.no/UserInterface/#/Datasetexplorer.imr.no	Data on request. Trawl, benthic sample, video and CTD sampling data from research surveys
	Seabirds and Marine mammals monitoring	https://seapop.no/aktiviteter/lokaliteter https://www.hi.no/hi/forskning/forskningsgrupper/sjopattedyr	Expert pers. Comm. Supplementary information; distribution maps and metadata
Telecommunication	Cables	https://kart.barentswatch.no/	
Marine transportation	Ship traffic	https://kart.barentswatch.no/	Ship traffic by vessel category
Tourism and recreation	Land-based recreation	https://kart.ssb.no	Population, holiday houses, potential recreation areas
	Boating/yatchting	https://kart.barentswatch.no/	Ship density from Emodnet (leisure boats with AIS)
Wastewater treatment	Sewage treatment and output location	https://vannmiljo.miljodirektoratet.no/	Map of treatment plants

Table A3
Description of categories used to score confidence for exposure (to pressures from sectors) and effect (of pressure on ecosystem components). Confidence for exposure was judged by the degree and quality of information available on the distributions in space and time of the assessed pressures and ecosystem components. Often, confidence for exposure needs to account for both the quality of information on sector activity, and the expected correlation between the spatial distribution of activities from a sector and a pressure associated with the activity. The assessment was based on confidence assessments described in (Robinson et al., 2013). Confidence for effects reflects the knowledge used to score the degree of impact (DoI) a pressure is expected to have on an ecosystem component and was here scored based on the vulnerability assessment with associated confidence scores in Hansen et al. (2022). This confidence scoring was based on the combination of robustness of evidence and level of agreement, as in the IPCC (Mastrandrea et al., 2011).

Confidence exposure	Description
3 - High	Relevant data or information were available for the area, and/or the group of experts agreed that they had high confidence in the assessment based on there being good information that underpinned the judgments made by the group even if some transfer of knowledge from different systems/cases had been required.
2 - Moderate	There was some relevant information or data, but it did not necessarily come from the assessed area and required some interpretation/extrapolation, and/or where there was some disagreement on how the information should be interpreted.
1 - Low	Relevant information was not available at all, and/or there was no agreement among the group of experts irrespective of the information available.
Confidence effect	**Description**
3 - High	Very high or high confidence in Hansen et al. (2022). High agreement combined with medium to robust evidence, or medium agreement and robust evidence.
2 - Moderate	Medium confidence in Hansen et al. (2022). High agreement but limited evidence, medium agreement and medium evidence, or low agreement combined with robust evidence.
1 - Low	Low or very low confidence in Hansen et al. (2022). Medium to low agreement combined with limited evidence, or low agreement combined with medium evidence.

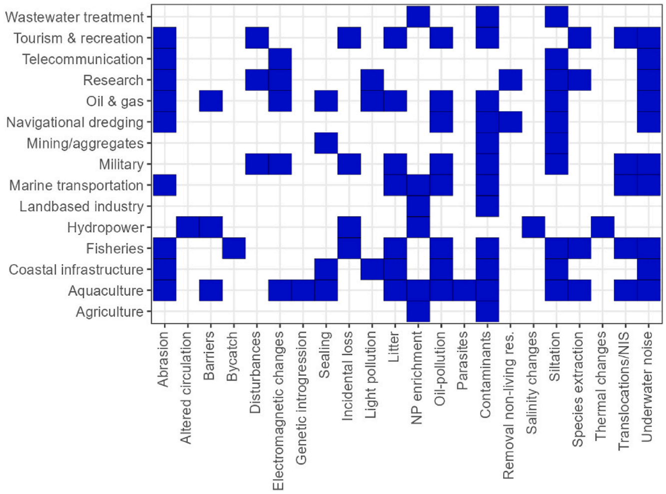

Fig. A1. Sector-pressure matrix linking the 16 coastal sectors to the pressures their activities impose on the marine environment.

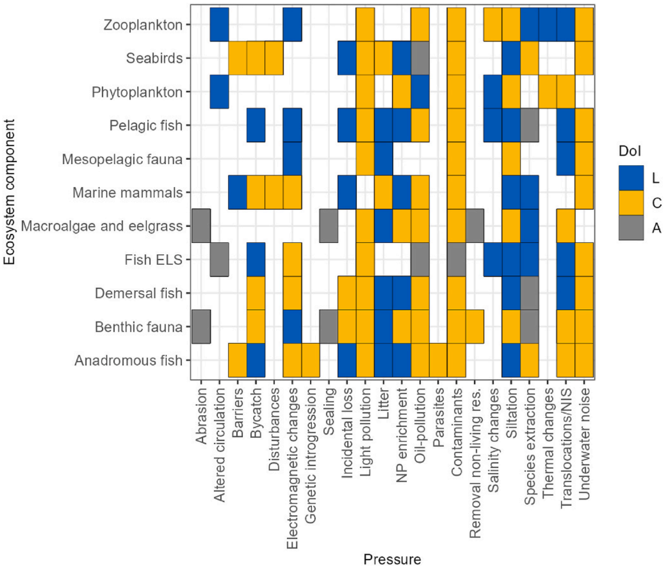

Fig. A2. Degree of impact (DoI) scored for the ecosystem components affected by the different pressures. DoI is scored as L (low), C (chronic) or A (acute), following the ODEMM definitions in (Robinson et al., 2013). The scorings here are to a large degree based on the vulnerability assessment carried out by Hansen et al. (2022), though some adjustments have been made to better comply with the definitions for the DoI categories in (Robinson et al., 2013). Note that anadrome fish has different DoI for the pressures barriers and incidental loss based on which sector the pressure arises from (not shown in fig.). Both are chronic when associated with hydropower, since water regulation may prevent many individuals simultaneously on their natural migration up rivers to spawn and individual fish suffer mortality when intending to pass through the turbines. For other sectors, the DoI is scored as low.

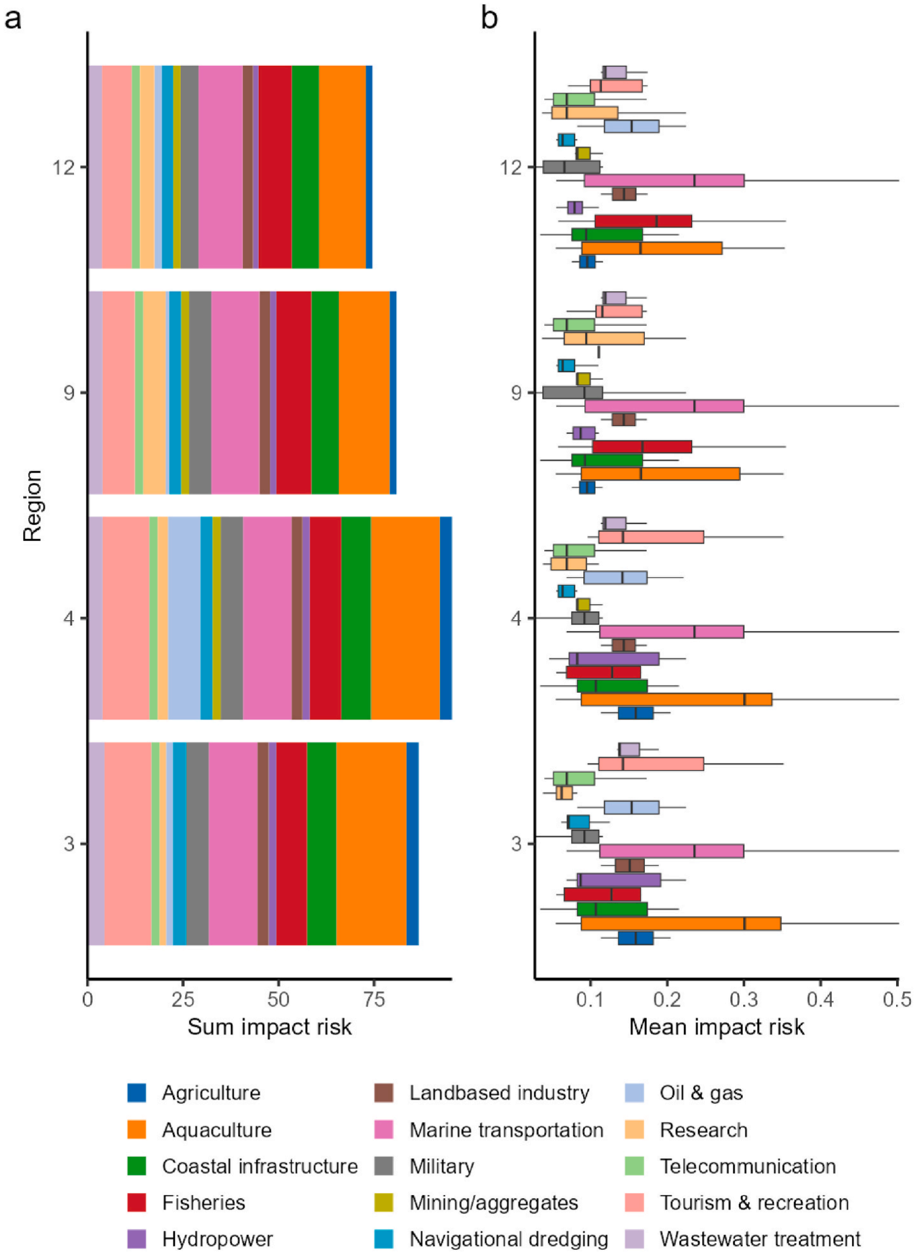

Fig. A3. a) Cumulative impact risk and b) mean impact risk per pressure, for the 15 sectors in the four regions using ordinal scores from Piet et al. (2017). Outliers in b) have been omitted to enhance visualization. Ordinal scorings give a higher weight to sectors like coastal infrastructure, which have a low contribution using weighted scores. Hence, the risk contribution by sector becomes more similar with ordinal compared to weighted scoring of the impact chains.

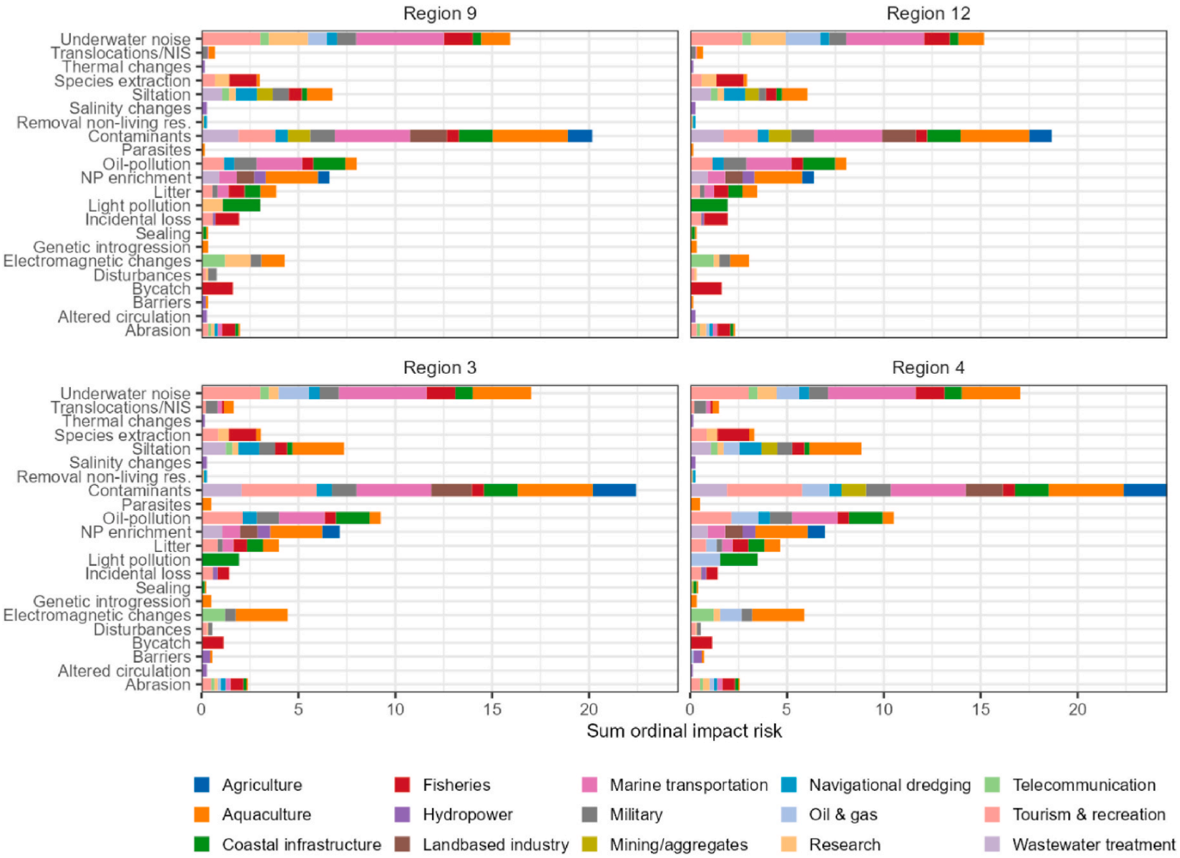

Fig. A4. Cumulative impact risk per pressure in the four regions, using ordinal scores from Piet et al. (2017). Columns are colored by the contribution from the different sectors. Ordinal scorings give a higher weight to pressures and sectors which have a low contribution using weighted scorings. Hence, the overall risk picture changes somewhat with ordinal scoring. NP: Nitrogen and Phosphorous.

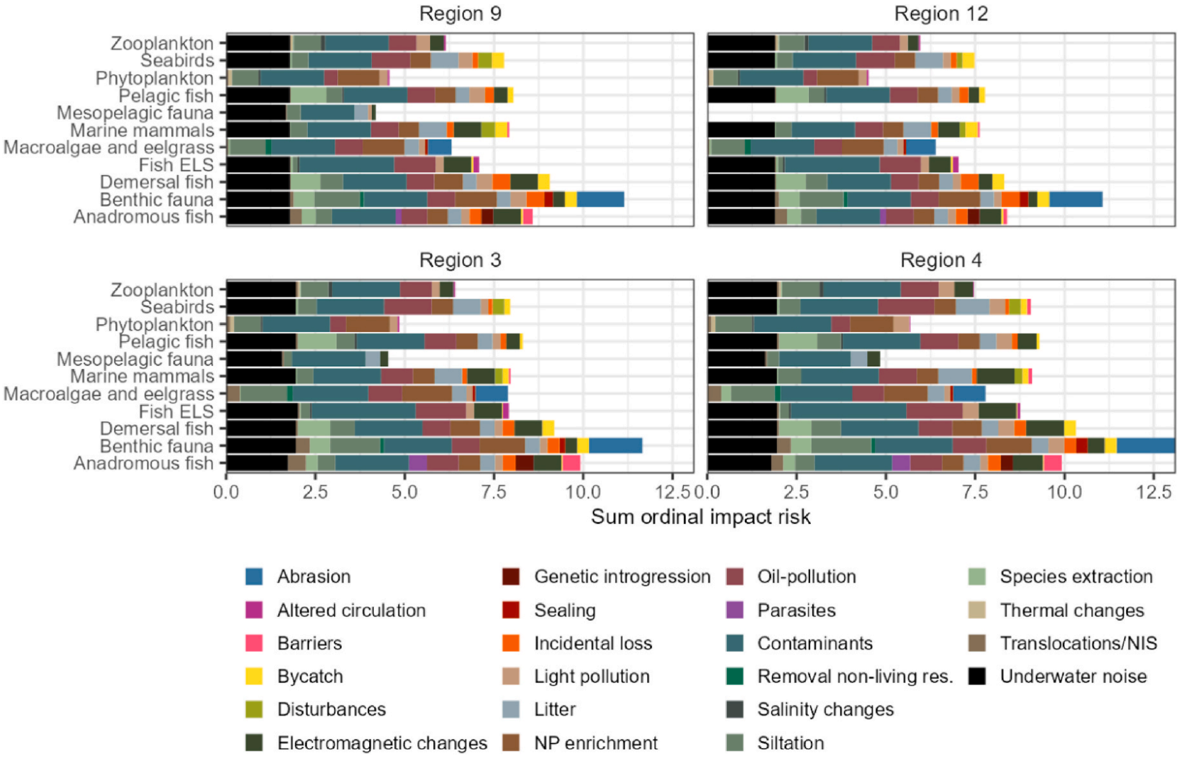

Fig. A5. Cumulative impact risk per ecosystem component in the four regions, using ordinal scores from Piet et al. (2017). Columns are colored by the contribution from the different pressures. Ordinal scorings give a higher weight to pressures which have a low contribution using weighted scores. Hence, the overall picture becomes more homogenous. NP: Nitrogen and Phosphorous.

References

Aandahl, P.T., Brækkan, E.H., 2023. Norge eksporterte sjømat for 151,4 milliarder kroner i 2022 [WWW Document]. Nor. Sjømatråd. URL. https://seafood.no/aktuelt/nyheter/norge-eksporterte-sjomat-for-1514-milliarder-kroner-i-2022/. (Accessed 17 July 2023).

Ådlandsvik, B., 2022. Havbruk til havs - yttergrense for produksjonsområdene, Rapport fra havforskningen (No. 2022–2). Institute of Marine Research.

Ådlandsvik, B., 2015. Forslag Til Produksjonsområder I Norsk Lakse- Og Ørretoppdrett, Report to the Norwegian Ministry of Industry, Trade and Fisheries. Institute of Marine Research.

Andersen, L.B., Grefsrud, E.S., Svåsand, T., Sandlund, N., 2022. Risk understanding and risk acknowledgement: a new approach to environmental risk assessment in marine aquaculture. ICES J. Mar. Sci. 79, 987–996.

Anonymous, 1987. Report of the World Commission on Environment and Development: Our Common Future. World Commission on Environment and Development.

Araújo, R.M., Assis, J., Aguillar, R., Airoldi, L., Bárbara, I., Bartsch, I., Bekkby, T., Christie, H., Davoult, D., Derrien-Courtel, S., Fernandez, C., Fredriksen, S., Gevaert, F., Gundersen, H., Le Gal, A., Lévêque, L., Mieszkowska, N., Norderhaug, K. M., Oliveira, P., Puente, A., Rico, J.M., Rinde, E., Schubert, H., Strain, E.M., Valero, M., Viard, F., Sousa-Pinto, I., 2016. Status, trends and drivers of kelp forests in Europe: an expert assessment. Biodivers. Conserv. 25, 1319–1348. https://doi.org/10.1007/s10531-016-1141-7.

Azad, A.M., Frantzen, S., Bank, M.S., Johnsen, I.A., Tessier, E., Amouroux, D., Madsen, L., Maage, A., 2019. Spatial distribution of mercury in seawater, sediment, and seafood from the Hardangerfjord ecosystem, Norway. Sci. Total Environ. 667, 622–637. https://doi.org/10.1016/j.scitotenv.2019.02.352.

Azad, A.M., Frantzen, S., Bank, M.S., Madsen, L., Maage, A., 2021. Mercury bioaccumulation pathways in tusk (*Brosme brosme*) from Sognefjord, Norway: insights from C and N isotopes. Environ. Pollut. 269, 115997 https://doi.org/10.1016/j.envpol.2020.115997.

Bailey, D.M., Hopkins, C.R., 2023. Sustainable use of ocean resources. Mar. Pol. 154, 105672 https://doi.org/10.1016/j.marpol.2023.105672.

Barbier, E.B., Hacker, S.D., Kennedy, C., Koch, E.W., Stier, A.C., Silliman, B.R., 2011. The value of estuarine and coastal ecosystem services. Ecol. Monogr. 81 (1), 169–193. https://doi.org/10.1890/10-1510.

Bjerck, H.B., Urke, H.A., Haugen, T.O., Alfredsen, J.A., Ulvund, J.B., Kristensen, T., 2021. Synchrony and multimodality in the timing of Atlantic salmon smolt migration in two Norwegian fjords. Sci. Rep. 11, 6504. https://doi.org/10.1038/s41598-021-85941-9.

Blasiak, R., Anderson, J.L., Bridgewater, P., Furuya, K., Halpern, B.S., Kurokura, H., Morishita, J., Yagi, N., Minohara, A., 2014. Paradigms of sustainable ocean management. Mar. Pol. 48, 206–211. https://doi.org/10.1016/j.marpol.2014.03.021.

Borgwardt, F., Robinson, L., Trauner, D., Teixeira, H., Nogueira, A.J.A., Lillebø, A.I., Piet, G., Kuemmerlen, M., O'Higgins, T., McDonald, H., Arevalo-Torres, J., Barbosa, A.L., Iglesias-Campos, A., Hein, T., Culhane, F., 2019. Exploring variability in environmental impact risk from human activities across aquatic ecosystems. Sci. Total Environ. 652, 1396–1408. https://doi.org/10.1016/j.scitotenv.2018.10.339.

Borja, A., Elliott, M., Andersen, J.H., Berg, T., Carstensen, J., Halpern, B.S., Heiskanen, A.-S., Korpinen, S., Lowndes, J.S.S., Martin, G., Rodriguez-Ezpeleta, N., 2016. Overview of integrative assessment of marine systems: the ecosystem approach in practice. Front. Mar. Sci. 3 https://doi.org/10.3389/fmars.2016.00020.

Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R.V., Paruelo, J., Raskin, R.G., Sutton, P., van den Belt, M., 1997. The value of the world's ecosystem services and natural capital. Nature 387, 253–260. https://doi.org/10.1038/387253a0.

Dahle, G., Johansen, T., Westgaard, J.-I., Aglen, A., Glover, K.A., 2018. Genetic management of mixed-stock fisheries "real-time": the case of the largest remaining cod fishery operating in the Atlantic in 2007–2017. Fish. Res. 205, 77–85. https://doi.org/10.1016/j.fishres.2018.04.006.

Dankel, D.J., Boonstra, W.J., Bjørkan, M., Fuller, J., Iversen, L., Eskeland Schütz, S., Staal, B., van der Meeren, G., van Putten, I., 2022. Localizing the sustainable development goals for marine and coastal management in Norway: a venture overdue. In: Human-Nature Interactions: Exploring Nature's Values across Landscapes. Springer International Publishing, pp. 343–359.

De Lange, H.J., Sala, S., Vighi, M., Faber, J.H., 2010. Ecological vulnerability in risk assessment — a review and perspectives. Sci. Total Environ., Cumulative Stressors - Risk assessment of mixtures of chemicals and combinations of chemicals and natural stressors 408, 3871–3879. https://doi.org/10.1016/j.scitotenv.2009.11.009.

Delgado-Serrano, M. del M., Ramos, P., 2015. Making Ostrom's framework applicable to characterise social ecological systems at the local level. Int. J. Commons 9, 808–830. https://doi.org/10.18352/ijc.567.

DNV, 2023. Spatial Competition Forecast, Ocean's Future to 2050. DNV.

DNV, 2021. Ocean's Future to 2050. DNV.

Duarte, C.M., 2022. Restoration and Potential of Blue Forest Globally.

Duarte, C.M., Chapuis, L., Collin, S.P., Costa, D.P., Devassy, R.P., Eguiluz, V.M., Erbe, C., Gordon, T.A.C., Halpern, B.S., Harding, H.R., Havlik, M.N., Meekan, M., Merchant, N.D., Miksis-Olds, J.L., Parsons, M., Predragovic, M., Radford, A.N., Radford, C.A., Simpson, S.D., Slabbekoorn, H., Staaterman, E., Opzeeland, I.C.V., Winderen, J., Zhang, X., Juanes, F., 2021. The soundscape of the Anthropocene ocean. Science 371. https://doi.org/10.1126/science.aba4658.

Duarte, C.M., Dennison, W.C., Orth, R.J.W., Carruthers, T.J.B., 2008. The charisma of coastal ecosystems: addressing the imbalance. Estuar. Coast 31, 233–238. https://doi.org/10.1007/s12237-008-9038-7.

Dybedal, P., 2018. Cruisetrafikk Til Norske Havner: Oversikt, Historie Og Prognoser 2018-2060, TØI Report No. 1651/2018. Institute of Transport Economics.

Elliott, M., Burdon, D., Atkins, J.P., Borja, A., Cormier, R., de Jonge, V.N., Turner, R.K., 2017. "And DPSIR begat DAPSI(W)R(M)!" - a unifying framework for marine environmental management. Mar. Pollut. Bull. 118, 27–40. https://doi.org/10.1016/j.marpolbul.2017.03.049.

Evenseth, A., Refseth, G.H., Dale, T., Arnberg, M., Harendza, A., Sagerup, K., Striberny, A., Izquiredo-Gomez, D., Borgersen, G., Bjorbekkmo, M.M., Pedersen, K. B., Mikkelsen, E., Eriksen, K., Emaus, P.A., Sparboe, L.-O., Iversen, A., 2023. Environmental Impacts of Aquaculture and Coexisting Industries, Akvaplan-Niva Rapport. No. 2023 63547.01).

Everaert, G., Ruus, A., Hjermann, D.Ø., Borgå, K., Green, N., Boitsov, S., Jensen, H., Poste, A., 2017. Additive models reveal sources of metals and organic pollutants in Norwegian marine sediments. Environ. Sci. Technol. 51, 12764–12773. https://doi.org/10.1021/acs.est.7b02964.

Faglig forum for norske havområder, 2022. Vurdering Av Måloppnåelse. Faggrunnlag for Helhetlige Forvaltningsplaner for Norske Havområder. No. M-2410 | 2022).

Grefsrud, E.S., Andersen, L.B., Grøsvik, B.E., Karlsen, Ø., Kvamme, B.O., Hansen, P.K., Husa, V., Sandlund, N., Stien, L.H., Solberg, M.F., 2023. Risikorapport norsk fiskeoppdrett 2022 - Produksjonsdødelighet hos oppdrettsfisk og miljøeffekter av norsk fiskeoppdrett, Rapport fra havforskningen, vols. 2023–6. Institute of Marine Research.

Halpern, B.S., 2020. Building on a decade of the Ocean Health Index. One Earth 2, 30–33. https://doi.org/10.1016/j.oneear.2019.12.011.

Halpern, B.S., Frazier, M., Afflerbach, J., Lowndes, J.S., Micheli, F., O'Hara, C., Scarborough, C., Selkoe, K.A., 2019. Recent pace of change in human impact on the world's ocean. Sci. Rep. 9, 11609 https://doi.org/10.1038/s41598-019-47201-9.

Halpern, B.S., Frazier, M., Potapenko, J., Casey, K.S., Koenig, K., Longo, C., Lowndes, J. S., Rockwood, R.C., Selig, E.R., Selkoe, K.A., Walbridge, S., 2015. Spatial and temporal changes in cumulative human impacts on the world's ocean. Nat. Commun. 6, 7615. https://doi.org/10.1038/ncomms8615.

Halpern, B.S., Walbridge, S., Selkoe, K.A., Kappel, C.V., Micheli, F., D'Agrosa, C., Bruno, J.F., Casey, K.S., Ebert, C., Fox, H.E., Fujita, R., Heinemann, D., Lenihan, H.S., Madin, E.M.P., Perry, M.T., Selig, E.R., Spalding, M., Steneck, R., Watson, R., 2008. A global map of human impact on marine ecosystems. Science 319, 948–952. https://doi.org/10.1126/science.1149345.

Hammar, L., Molander, S., Pålsson, J., Schmidtbauer Crona, J., Carneiro, G., Johansson, T., Hume, D., Kågesten, G., Mattsson, D., Törnqvist, O., Zillén, L., Mattsson, M., Bergström, U., Perry, D., Caldow, C., Andersen, J.H., 2020. Cumulative impact assessment for ecosystem-based marine spatial planning. Sci. Total Environ. 734, 139024 https://doi.org/10.1016/j.scitotenv.2020.139024.

Hansen, C., Hjøllo, S.S., Ottersen, G., Skern-Mauritzen, M., 2022. Miljøverdiers sårbarhet i norske havområder, Rapport fra havforskningen (No. 2022–33). Institute of Marine Research.

Holling, C.S., 1973. Resilience and stability of ecological systems. Annu. Rev. Ecol. Systemat. 4, 1–23. https://doi.org/10.1146/annurev.es.04.110173.000245.

Holsman, K., Samhouri, J., Cook, G., Hazen, E., Olsen, E., Dillard, M., Kasperski, S., Gaichas, S., Kelble, C.R., Fogarty, M., Andrews, K., 2017. An ecosystem-based approach to marine risk assessment. Ecosyst. Health Sustain 3, e01256. https://doi.org/10.1002/ehs2.1256.

Jakobsen, E.W., Mellbye, C.S., Haugland, L.M., Osman, M.S., Villemin, A., 2018. The Leading Maritime Nations of the World 2018, Joint Menon Economics and DNV-GL Publications. Menon Economics and DNV-GL.

Jalkanen, J.-P., Johansson, L., Andersson, M.H., Majamäki, E., Sigray, P., 2022. Underwater noise emissions from ships during 2014-2020. Environ. Pollut. 311, 119766 https://doi.org/10.1016/j.envpol.2022.119766.

Jensen, J.L.A., Strøm, J.F., Nikolopoulos, A., Primicerio, R., Skarðhamar, J., Atencio, B. J., Strand, J.E.T., Bjørn, P.A., Bøhn, T., 2022. Micro- and macro-habitat selection of Atlantic salmon, *Salmo salar*, post-smolts in relation to marine environmental cues. ICES J. Mar. Sci. 79, 1394–1407. https://doi.org/10.1093/icesjms/fsac064.

Johansson, L., Ytreberg, E., Jalkanen, J.-P., Fridell, E., Eriksson, K.M., Lagerström, M., Maljutenko, I., Raudsepp, U., Fischer, V., Roth, E., 2020. Model for leisure boat activities and emissions – implementation for the Baltic Sea. Ocean Sci 16, 1143–1163. https://doi.org/10.5194/os-16-1143-2020.

Jouffray, J.-B., Blasiak, R., Norström, A.V., Österblom, H., Nyström, M., 2020. The blue acceleration: the trajectory of human expansion into the Ocean. One Earth 2, 43–54. https://doi.org/10.1016/j.oneear.2019.12.016.

Judd, A.D., Backhaus, T., Goodsir, F., 2015. An effective set of principles for practical implementation of marine cumulative effects assessment. Environ. Sci. Pol. 54, 254–262. https://doi.org/10.1016/j.envsci.2015.07.008.

Kaltenborn, B.P., Kaltenborn, E.F., Linnell, J.D.C., 2019. "It's all about the scenery": tourists' perceptions of cultural ecosystem services in the lofoten islands, Norway. Arctic 72, 1–12. https://doi.org/10.14430/arctic67944.

Klemetsen, A., Amundsen, P.-A., Dempson, J.B., Jonsson, B., Jonsson, N., O'Connell, M. F., Mortensen, E., 2003. Atlantic salmon *Salmo salar* L., brown trout *Salmo trutta* L. and Arctic charr *Salvelinus alpinus* (L.): a review of aspects of their life histories. Ecol. Freshw. Fish 12, 1–59. https://doi.org/10.1034/j.1600-0633.2003.00010.x.

Knights, A.M., Koss, R.S., Robinson, L.A., 2013. Identifying common pressure pathways from a complex network of human activities to support ecosystem-based management. Ecol. Appl. 23, 755–765. https://doi.org/10.1890/12-1137.1.

Knights, A.M., Piet, G.J., Jongbloed, R.H., Tamis, J.E., White, L., Akoglu, E., Boicenco, L., Churilova, T., Kryvenko, O., Fleming-Lehtinen, V., Leppanen, J.-M., Galil, B.S., Goodsir, F., Goren, M., Margonski, P., Moncheva, S., Oguz, T., Papadopoulou, K.N., Setälä, O., Smith, C.J., Stefanova, K., Timofte, F., Robinson, L.A., 2015. An exposure-effect approach for evaluating ecosystem-wide risks from human activities. ICES J. Mar. Sci. 72, 1105–1115. https://doi.org/10.1093/icesjms/fsu245.

Korpinen, S., Andersen, J.H., 2016. A global review of cumulative pressure and impact assessments in marine environments. Front. Mar. Sci. 3 https://doi.org/10.3389/fmars.2016.00153.

Korpinen, S., Laamanen, L., Bergström, L., Nurmi, M., Andersen, J.H., Haapaniemi, J., Harvey, E.T., Murray, C.J., Peterlin, M., Kallenbach, E., Klančnik, K., Stein, U., Tunesi, L., Vaughan, D., Reker, J., 2021. Combined effects of human pressures on Europe's marine ecosystems. Ambio 50, 1325–1336. https://doi.org/10.1007/s13280-020-01482-x.

Kristoffersen, B., Midtgard, M.R., 2016. Lofoten Som Reiselivsdestinasjon I Dag Og I Framtida - Turistens Perspektiv [Lofoten as Travel Destination Today and in the Future - the Tourist's Perspective], SINTEF Rapport (No. 4/2016). SINTEF.

Kühn, S., King, F., Heubel, K., 2023. Decreased feeding rates of the copepod *Acartia tonsa* when exposed to playback harbor traffic noise. Front. Mar. Sci. 10 https://doi.org/10.3389/fmars.2023.1134792.

Kvamstad-Lervold, B., Holte, E.A., Johansen, U., 2019. Fremtidsmuligheter i maritime næringer (No. OC2019 A-120), Sintef Ocean AS. Sintef Ocean AS 72.

Levin, P.S., Kelble, C.R., Shuford, R.L., Ainsworth, C., deReynier, Y., Dunsmore, R., Fogarty, M.J., Holsman, K., Howell, E.A., Monaco, M.E., Oakes, S.A., Werner, F., 2014. Guidance for implementation of integrated ecosystem assessments: a US perspective. ICES J. Mar. Sci. 71, 1198–1204. https://doi.org/10.1093/icesjms/fst112.

Lu, Y., Yuan, J., Lu, X., Su, C., Zhang, Y., Wang, C., Cao, X., Li, Q., Su, J., Ittekkot, V., Garbutt, R.A., Bush, S., Fletcher, S., Wagey, T., Kachur, A., Sweijd, N., 2018. Major threats of pollution and climate change to global coastal ecosystems and enhanced management for sustainability. Environ. Pollut. 239, 670–680. https://doi.org/10.1016/j.envpol.2018.04.016.

Mastrandrea, M.D., Mach, K.J., Plattner, G.-K., Edenhofer, O., Stocker, T.F., Field, C.B., Ebi, K.L., Matschoss, P.R., 2011. The IPCC AR5 guidance note on consistent treatment of uncertainties: a common approach across the working groups. Clim. Change 108, 675. https://doi.org/10.1007/s10584-011-0178-6.

Norwegian Ministry of Petroleum and Energy, 2021. Energi til arbeid - langsiktig verdiskaping fra norske energiressurser (White paper No. 36 (2020-2021)).

Norwegian Ministry of Trade, Industry and Fisheries, 2021. Havbruksstrategien - Et Hav Av Muligheter (Government strategy paper).

OECD, 1994. Environmental Indicators: OECD Core Set. Organisation for Economic Co-operation and Development, Paris.

Pauly, D., Christensen, V., 1995. Primary production required to sustain global fisheries. Nature 374, 255–257. https://doi.org/10.1038/374255a0.

Pedreschi, D., Bouch, P., Moriarty, M., Nixon, E., Knights, A.M., Reid, D.G., 2019. Integrated ecosystem analysis in Irish waters; Providing the context for ecosystem-based fisheries management. Fish. Res. 209, 218–229. https://doi.org/10.1016/j.fishres.2018.09.023.

Pedreschi, D., Niiranen, S., Skern-Mauritzen, M., Reid, D.G., 2023. Operationalising ODEMM risk assessment for integrated ecosystem assessment scoping: complexity vs. manageability. Front. Mar. Sci. 9 https://doi.org/10.3389/fmars.2022.1037878.

Piet, G., Grundlehner, A., Jongbloed, R., Tamis, J., de Vries, P., 2023. SCAIRM: a spatial cumulative assessment of impact risk for management. Ecol. Indicat. 157, 111157 https://doi.org/10.1016/j.ecolind.2023.111157.

Piet, G.J., Jongbloed, R.H., Knights, A.M., Tamis, J.E., Paijmans, A.J., van der Sluis, M.T., de Vries, P., Robinson, L.A., 2015. Evaluation of ecosystem-based marine management strategies based on risk assessment. Biol. Conserv. 186, 158–166. https://doi.org/10.1016/j.biocon.2015.03.011.

Piet, G.J., Knights, A.M., Jongbloed, R.H., Tamis, J.E., de Vries, P., Robinson, L.A., 2017. Ecological risk assessments to guide decision-making: methodology matters. Environ. Sci. Pol. 68, 1–9. https://doi.org/10.1016/j.envsci.2016.11.009.

Rikardsen, A.H., Righton, D., Strøm, J.F., Thorstad, E.B., Gargan, P., Sheehan, T., Økland, F., Chittenden, C.M., Hedger, R.D., Næsje, T.F., Renkawitz, M., Sturlaugsson, J., Caballero, P., Baktoft, H., Davidsen, J.G., Halttunen, E., Wright, S., Finstad, B., Aarestrup, K., 2021. Redefining the oceanic distribution of Atlantic salmon. Sci. Rep. 11, 12266 https://doi.org/10.1038/s41598-021-91137-y.

Robinson, L.A., Culhane, F.E., 2020. Linkage frameworks: an exploration tool for complex systems in ecosystem-based management. In: O'Higgins, T.G., Lago, M., DeWitt, T.H. (Eds.), Ecosystem-Based Management, Ecosystem Services and Aquatic Biodiversity : Theory, Tools and Applications. Springer International Publishing, Cham, pp. 213–233. https://doi.org/10.1007/978-3-030-45843-0_11.

Robinson, L.A., Culhane, F.E., Baulcomb, C., Bloomfield, H., Boehnke-Henrichs, H., Breen, P., Goodsir, F., Hussain, S.S., Knights, A.M., Raakjær, J., van Tatenhove, J., Frid, C.L.J., 2014. Towards Delivering Ecosystem-Based Marine Management: the ODEMM Approach, Deliverable 17, EC FP7 Project (244273), "Options for Delivering Ecosystem-Based Marine Management.".

Robinson, L.A., White, L., Culhane, F., Knights, A.M., 2013. ODEMM pressure assessment userguide V.2. (No. 4), ODEMM guidance document series. EC FP7 Project (244273) "Options for Delivering Ecosystem-Based Marine Management.". University, of Liverpool.

Ryther, J.H., 1969. Photosynthesis and fish production in sea: the production of organic matter and its conversion to higher forms of life vary throughout the world ocean. Science 166, 72–76. https://doi.org/10.1126/science.166.3901.72.

Sætre, R., Gjertsen, K., Bröker, K., 2007. The Norwegian Coastal Current: Oceanography and Climate. Tapir Academic Press Institute of Marine Research, Trondheim.

Smith, A.D.M., Fulton, E.J., Hobday, A.J., Smith, D.C., Shoulder, P., 2007. Scientific tools to support the practical implementation of ecosystem-based fisheries management. ICES J. Mar. Sci. 64, 633–639. https://doi.org/10.1093/icesjms/fsm041.

Stelzenmüller, V., Coll, M., Mazaris, A.D., Giakoumi, S., Katsanevakis, S., Portman, M.E., Degen, R., Mackelworth, P., Gimpel, A., Albano, P.G., Almpanidou, V., Claudet, J., Essl, F., Evagelopoulos, T., Heymans, J.J., Genov, T., Kark, S., Micheli, F., Pennino, M.G., Rilov, G., Rumes, B., Steenbeek, J., Ojaveer, H., 2018. A risk-based approach to cumulative effect assessments for marine management. Sci. Total Environ. 612, 1132–1140. https://doi.org/10.1016/j.scitotenv.2017.08.289.

Stephens, T., 2023. The kunming–montreal global biodiversity framework. Int. Leg. Mater. 62, 868–887. https://doi.org/10.1017/ilm.2023.16.

Taranger, G.L., Karlsen, Ø., Bannister, R.J., Glover, K.A., Husa, V., Karlsbakk, E., Kvamme, B.O., Boxaspen, K.K., Bjørn, P.A., Finstad, B., Madhun, A.S., Morton, H.C., Svåsand, T., 2015. Risk assessment of the environmental impact of Norwegian Atlantic salmon farming. ICES J. Mar. Sci. 72, 997–1021. https://doi.org/10.1093/icesjms/fsu132.

Turschwell, M., Hayes, M., Lacharité, M., Abundo, M., Adams, J., Blanchard, J., Brain, E., Buelow, C., Bulman, C., Condie, S., Connolly, R., Dutton, I., Fulton, E., Gallagher, S., Maynard, D., Pethybridge, H., Plagányi, E., Porobic, J., Taelman, S., Trebilco, R., Woods, G., Brown, C., 2022. A review of support tools to assess multi-sector interactions in the emerging offshore Blue Economy. Environ. Sci. Pol. 133, 203–214. https://doi.org/10.1016/j.envsci.2022.03.016.

Varpe, Ø., Fiksen, Ø., Slotte, A., 2005. Meta-ecosystems and biological energy transport from ocean to coast: the ecological importance of herring migration. Oecologia 146, 443–451. https://doi.org/10.1007/s00442-005-0219-9.

Villasante, S., Richter, K., Bailey, J., Bleckner, T., Farrell, E., Mongruel, R., Timmermann, K., Bouma, T., Melaku Canu, D., Chen, M., Lachs, L., Payo, A., Sousa Pinto, I., 2023. Building Coastal Resilience in Europe (No. Position Paper No. 27 of the European Marine Board). European Marine Board, Ostend, Belgium.

Vollset, K.W., Nilsen, F., Ellingsen, I., Karlsen, Ø., Paterson, R.A., Qviller, L., Skardhamar, J., Stige, L.C., Sægrov, H., Ugedal, O., Dalvin, S., 2022. Produksjonsområdebasert vurdering av lakselusindusert villfiskdødelighet i 2022. Rapport fra ekspertgruppe for vurdering av lusepåvirkning. Trondheim.

World Bank, 2017. The Potential of the Blue Economy: Increasing Long-Term Benefits of the Sustainable Use of Marine Resources for Small Island Developing States and Coastal Least Developed Countries. World Bank and United Nations Department of Economic and Social Affairs, Washington DC.

Ytreberg, E., Hansson, K., Hermansson, A.L., Parsmo, R., Lagerström, M., Jalkanen, J.-P., Hassellöv, I.-M., 2022. Metal and PAH loads from ships and boats, relative other sources, in the Baltic Sea. Mar. Pollut. Bull. 182, 113904. https://doi.org/10.1016/j.marpolbul.2022.113904.