frontiers | Frontiers in Marine Science

TYPE Original Research
PUBLISHED 23 December 2022
DOI 10.3389/fmars.2022.975328

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SPECIALTY SECTION
This article was submitted to
Marine Conservation and
Sustainability,
a section of the journal
Frontiers in Marine Science

RECEIVED 22 June 2022
ACCEPTED 09 December 2022
PUBLISHED 23 December 2022

CITATION
Skein L, Sink KJ, Majiedt PA,
van der Bank MG, Smit KP and
Shannon LJ (2022) Scoping an
integrated ecosystem assessment for
South Africa.
Front. Mar. Sci. 9:975328.
doi: 10.3389/fmars.2022.975328

Scoping an integrated ecosystem assessment for South Africa

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The need to move toward marine ecosystem-based management is globally recognized. Few countries effectively account for multiple interacting pressures in their marine assessments, planning and management. Many socio-economic sectors currently operate in South African waters and in most cases, their associated pressures are managed on a sector-by-sector basis and interacting pressures are seldom accounted for in assessments or decision-making. For ecosystem-based management to be effective, a science-based approach to prioritize sectors and pressures needing most urgent action, and to identify affected ecological components is needed. Integrated Ecosystem Assessment (IEA) has hence been put forward as a tool that can organize relevant information and provide context for cross-sectoral management decisions. Consisting of five main stages that form an iterative cycle, the first IEA stage involves scoping of top management priorities in a given area and can be done by way of risk assessment. Through the ODEMM (Options for Delivering Ecosystem-based Marine Management) approach, linkage chains (interactions) among sectors, pressures and affected ecological components for the entirety of the South African marine territory were identified. Subsequently, impact risk scores of each linkage chain were calculated based on the exposure and severity of impacts faced by ecological components from pressures that are associated with each sector. *Fishing* was the sector with the greatest connectivity (11.65% proportional connectance) in the framework and ranked highest in terms of impact risk (summed), followed by *Shipping* and *Coastal infrastructure*. Pressures with the most serious impacts on ecological components, as identified through summed impact risk scores, included *Bycatch, Species extraction*, and *Incidental loss* and the ecological components most affected were those primarily associated with *Fishing* and its associated pressures. These findings align with those of the recent South

African National Biodiversity Assessment and corroborate views of local stakeholders. This study also identified key local knowledge gaps, including impacts of underwater noise, invasive species, and climate change, that must be better understood to improve assessment accuracy and guide management prioritization of pressures exerted by most impactful sectors.

KEYWORDS
cumulative pressures, ecosystem-based management, fisheries management, integrated ecosystem assessment, risk assessment

Introduction

Marine ecosystem degradation and declines in biodiversity (McCauley et al., 2015), accompanied by increases in cumulative impacts from human activity (Halpern et al., 2019) are among the main motivations prompting a shift from traditional economic sector- and species-specific management toward an ecosystem-level approach (Rosenberg and McLeod, 2005). Ecosystem-based management (EBM), that is, the cohesive management of entire ecosystems as opposed to its individual components (McLeod et al., 2005; Leslie and McLeod, 2007), recognizes interactions among ecosystem components, human sectors (economic and social) and the cumulative impacts generated by multiple sectors (Rosenberg and McLeod, 2005).

In light of the clearly demonstrated ecosystem-wide impacts of fisheries, the need to transition toward EBM has been greatly emphasized in this sector, with guidance to implement such management made available some 20 years ago (FAO, 2003). In South Africa, the initial transition to EBM focused on the Ecosystem Approach to Fisheries (EAF), defined by the FAO (2003) as an approach that “strives to balance diverse societal objectives, by taking account of the knowledge and uncertainties about biotic, abiotic and human components of ecosystems and their interactions and applying an integrated approach to fisheries within ecologically meaningful boundaries”. Several scientific approaches to understand the ecological context in which South African fisheries operate have been explored (Shannon et al., 2010) and can provide the scientific basis required for an EAF. In essence, EBM (and by extension the EAF) focuses on habitats and ecosystem integrity and is therefore area-based, whereas traditional fisheries management is sector-based, focusing on target resources (FAO, 2003). As such, management must balance trade-offs between ecosystem protection with socio-economic needs. Spatial approaches (e.g. marine spatial planning; Grimmel et al., 2019; DFFE, 2021) are particularly effective in seeking such trade-offs when the resource uses are themselves spatially delimited. Examples of spatial regulation of fisheries include spatially-explicit catch quotas (Prince et al., 2008), fleet zoning (Castilla, 2010) and gear restrictions (Murawski et al., 2000). Although existing South African legislation provides for MSP that can advance EBM, such regulations are rarely implemented (Reed et al., 2020), as is also the case elsewhere (Skern-Mauritzen et al., 2016). Indeed, although there tends to be general agreement among managers and policy makers on the theoretical premise of EBM, the practical implementation thereof can be complex and daunting (Hobday et al., 2011; Borja et al., 2016; Harvey et al., 2017).

Importantly, true EBM must acknowledge the effects of all sectors (not just fisheries in the marine case) that operate in an ecosystem (Harvey et al., 2017), integrating potential synergistic interactions and cumulative effects so that counter-productive sector- or resource-specific management may be avoided (Levin et al., 2009). Marine ecosystem assessments that underpin management decisions must therefore take a systematic, integrated approach to promote holistic management that will maintain the benefits of healthy marine ecosystems (Borja et al., 2016; Pavlidou et al., 2019; Kazanidis et al., 2020). Integrated Ecosystem Assessment (IEA) has been put forth as a framework to organize all information relevant to an ecosystem, so that EBM decisions at multiple scales and across sectors may be informed (Levin et al., 2009; Samhouri et al., 2014). Levin et al. (2009) defines IEA as “a formal synthesis and quantitative analysis of information on relevant natural and socio-economic factors, in relation to specified ecosystem management objectives”. It is an iterative cycle comprised of five main stages, namely: (1) scoping, where management goals and targets are defined, (2) indicator development, where ecosystem state is assessed and validated using suites of indicators that are ecologically relevant and applicable in a management context, (3) risk analysis, where risks to indicators developed in (2) are investigated, (4) management strategy evaluation, where the effectiveness of management strategies to address risks to indicators are evaluated, and (5) monitoring and evaluation, that consists of continuous monitoring of indicators to evaluate the effectiveness of management strategies (Levin et al., 2009; Samhouri et al., 2014). Importantly, this approach can be used to continuously re-evaluate the effectiveness of management in achieving refined objectives, assuming that such management is adaptable (Levin et al., 2009; Levin et al., 2014; Samhouri et al., 2014).

Ecological risk assessments, generally used to describe the likelihood and consequences of an event (Williams et al., 2011), have an important role in EBM (Hope, 2006). In this context, risk assessments may be used to assess the degree to which human activity may hinder the achievement of management objectives related to specific ecological components (Hobday et al., 2011; Samhouri and Levin, 2012). Ecological risk assessments are an integral component of IEA, and various types of assessments can be utilized throughout the IEA cycle, using a broad range of input data and knowledge generation (Treffny and Beilin, 2011; Arsenault et al., 2019; Poto et al., 2021). Holsman et al. (2017) categorizes risk assessments into three levels namely qualitative (e.g. Cook et al., 2014; Knights et al., 2015), semi-quantitative (e.g. Morzaria-Luna et al., 2014) and quantitative (e.g. Burgess et al., 2013). In the first IEA stage (scoping), where initial management priorities are identified, risk assessment can indicate which ecological components are most at risk from impacts produced by various sectors. Importantly, this step also involves stakeholders to ensure that the priorities identified through scoping incorporate stakeholder views and can greatly influence the decision-making environment at a later stage (Levin et al., 2009; Treffny and Beilin, 2011). A combination of qualitative and semi-quantitative approaches are utilized in scoping to provide a comprehensive view of all sectors, their associated pressures and the affected ecological components. These interactions can be weighted to provide information on relative risks and so that areas of greatest concern may be identified. At a later stage in the IEA cycle, quantitative model-based approaches can be utilized to evaluate the trade-offs and effectiveness of management scenarios in addressing key priorities, for example (Borja et al., 2016).

The Options for Delivering Ecosystem-based Marine Management (ODEMM) (https://odemm.com/) approach offers a framework to guide EBM and is based on key principles underlying EBM (Robinson et al., 2014) and IEA (Levin et al., 2009), and builds on elements of the DPSIR (Drivers, Pressures, State, Impact, Response; Atkins et al., 2011) approach. It was designed as a tool that places ecological risks in context so that management measures may be evaluated and optimized (Robinson et al., 2014). It incorporates key IEA phases, including scoping, where links between sectors, the pressures they are associated with, and the ecological components affected by these pressures (i.e. linkage chains as per Knights et al., 2013; Knights et al., 2015) are identified. This provides a holistic picture (a linkage framework) of a fully connected ecosystem inclusive of human activity. It can reveal, for example, sectors that share similar pressures, sectors with the most pressures, which ecological components are exposed to which pressures that may be having interactive effects, and the potential implications of such effects on multiple ecosystem services (Knights et al., 2013; Robinson et al., 2014; Knights et al., 2015). As not all linkage chains will result in the same degree of impact, weighting is required so that those interactions posing the greatest risk to ecosystems may be identified and prioritized for management. Individual linkage chains are subsequently scored based on the exposure of a pressure (as exerted by a particular sector) to an ecological component and the severity of its impact on said ecological component (Knights et al., 2013; Knights et al., 2015). Importantly, the ODEMM approach notes knowledge confidence with which scores are assigned to illuminate knowledge gaps and areas where expert stakeholder engagement is needed. This approach provides context for management and may reveal previously underestimated sectors and/or ecological components experiencing interacting and potentially cumulative pressures. For example, in Pedreschi et al. (2019), this approach revealed that after *Fishing*, several land-based industries were contributing to notable pressures in Irish waters, in this case highlighting that efficient marine EBM depends on synergistic management approaches from marine, terrestrial and freshwater realms.

To date, research advocating for EBM in South Africa has been fisheries-focused. If we are to move toward true EBM, we need to first synthesize all information relevant to South Africa's marine territory to provide context for realistic, efficient EBM to operate from in the future. A synthesis of all socio-economic sectors (ocean- and land-based) and the specific impacts they have on key ecological components in our marine territory can be achieved by means of IEA that provides guidance for a systematic organization of relevant information. In this study, we present results for the first IEA scoping assessment performed for the South African marine territory utilizing the ODEMM approach. Our aims were (1) to synthesize and assess the current state of knowledge on relevant sectors and their pressures on ecological components, (2) to identify linkage chains presenting greatest risk to ecological components, (3) to engage with local stakeholders on the IEA scoping results and establish if stakeholders are in agreement with key outcomes, and (4) to consider the relevance of priority actions identified in the latest National Biodiversity Assessment (NBA; Sink et al., 2019a) in light of the scoping results. This work was done as part of the Horizon 2020 Mission Atlantic project (https://missionatlantic.eu/), that aims to advance IEAs for the Atlantic ocean basin, and where South Africa is one of seven regional case-studies.

Methodology

ODEMM risk assessment

A linkage framework (Knights et al., 2013; Robinson et al., 2013) depicting all potential interactions in the ecosystem was first produced. This was done by establishing which sectors are associated with which pressures, and the ecological components that are affected by said pressures. The protocol outlined in Robinson et al. (2014) and associated ODEMM online resources (https://odemm.com/) provides general categories of sectors, pressures and ecological components applicable to most marine territories. However, components may be modified, added or removed to better represent the case-study area under question. As per Robinson et al. (2013), a pressure in this context is defined as "the mechanism through which an activity has an effect on any part of the ecosystem", and ecological components as "ecologically coherent elements of an ecosystem that group together more disparate taxonomic groups into the minimum number of elements, based on the view that the lower the number of elements, the easier it is to gain a coherent and integrated assessment across the ecosystem". For example, bottom trawling fisheries (sector) is associated with abrasion (pressure) of benthic habitats (ecological component) that can result in habitat degradation (impact exerted through the pressure). However, it is recognized that this aggregation or disaggregation approach is likely to elicit a trade-off between capturing the complexities of the ecosystem and ease of application, at the cost of misrepresenting the system.

At this stage no scores were assigned but merely the presence of an interaction in a sector-pressure-ecological component chain. Sectors, pressures and ecological components included in this assessment were those relevant in the South African marine context and therefore differ somewhat from those in the original ODEMM guidelines (Supplementary Material Tables 2-4). Broadly speaking, ecological components were divided into pelagic and benthic habitat types and the major taxonomic groups found in each habitat type. In addition, our assessment was refined to consider impacts documented within the last 20 years so that impacts assessed are relevant in terms of present management options. Linkage chains considered only direct impacts on ecological components, not indirect impacts. For example, fishing (sector) and species extraction (pressure) and its potential impacts on the food supply for marine mammals or seabirds (ecological components) was considered an indirect impact and not included in the linkage framework.

Once established, each sector-pressure-ecological component chain was given scores for each of three categories: (1) spatial overlap of a sector-pressure combination, (2) frequency of occurrence of a sector-pressure combination, and (3) the degree of impact of a sector-pressure combination on an ecological component (Table 1). Scores consist of standardized values based on raw values determined through a set of criteria. Further details and descriptions of the criteria for the different categories are provided in Knights et al. (2013); Robinson et al. (2013) and additional explanations provided as supplementary material (Supplementary Table 1) that support the rationale behind scores depicted in Table 1. The information underpinning these scores was largely derived from the most recent NBA (Sink et al., 2019a). For most sectors in this study, the NBA gathered recent information on spatio-temporal operational extent of marine sectors from academic institutions, government and industry. Spatial layers of sectoral activity were overlaid with the South African marine ecosystem map to guide scoring on all three categories used in this assessment. Some sectors were not included in the NBA, in which case literature, other forms of spatial data or expert opinion was used to guide scoring.

Confidence of supporting knowledge

The evidence supporting scores in each linkage chain was also categorized and could be either expert opinion, international literature support, or local literature support, the latter considered as the highest level of knowledge confidence. A snowballing approach to literature search was taken, and types of literature support included grey literature (e.g. environmental monitoring reports) and literature published in peer-reviewed scientific journals. This was useful to assess current shortcomings and to provide context in which findings could be interpreted.

Analyses

Following ODEMM guidelines, the proportional connectance of each sector, pressure and ecological component in the framework was calculated, in addition to Impact Risk (IR) that was calculated for each linkage chain (the product of spatial overlap, frequency of occurrence and degree of impact scores). IR describes the "likelihood of an adverse ecological impact following a sector-pressure interaction", and where "the greater the IR score, the greater the threat to the [ecological] component" (Knights et al., 2015). IR scores were subsequently log-transformed so that scores and their respective ranks could be better visualized. Top risks to the ecosystem were identified by considering (a) the mean of IR scores within the linkage framework, (b) sum of IR scores, and/or (c) the top scoring individual linkage chains (Piet et al., 2015). Options (a) and (b) may be influenced by the number of linkage chains in the framework, although (b) will be less sensitive to fluctuations in this number. For this reason both options are presented, in addition to the top scoring individual linkage chains (option c).

TABLE 1 Definitions and numerical scores associated with three categories (spatial overlap, frequency of occurrence, degree of impact) that were used to assess exposure (spatial overlap, frequency of occurrence) and severity (degree of impact) of each linkage chain in the framework (adapted from Robinson et al., 2013).

Exposure				
Spatial overlap *Spatial extent of overlap between a pressure and an ecological component*	**NO (score = 0):** no overlap between sector-pressure-ecological component, chain not considered further in the network	**SITE (score = 0.03):** Sector overlaps an ecological component, but less than 5%	**LOCAL (score = 0.37):** Sector overlaps an ecological component by more than 5% but less than 50%	**WIDESPREAD (score = 1):** Sector overlaps an ecological component by 50% or more
Frequency of occurrence *How often a pressure type and ecological component interaction occurs (months/year), regardless of the magnitude of the interaction.*	**RARE (score = 0.08):** Pressure introduced *via* sector up to 1 month a year	**OCCASIONAL (score = 0.33):** Pressure introduced *via* sector up to 4 months a year	**COMMON (score = 0.67):** Pressure introduced *via* sector up to 8 months a year	**PERSISTENT (score = 1):** Pressure introduced *via* sectors throughout an entire year
Severity				
Degree of impact *Generic sensitivity of an ecological characteristic to a pressure, regardless of the spatial overlap or frequency of occurrence.*	**LOW (score = 0.01):** Never causes high levels of mortality or habitat loss/never causes a noticeable effect for the ecosystem component of interest in the area of interaction.	**CHRONIC (score = 0.13):** Impact could have detrimental consequences if it occurs often enough/ at high enough levels	**ACUTE (score = 1):** Severe impact over a short duration. An interaction that kills a large proportion of individuals and causes an immediate change in the ecological component	

Individual linkage chains that contribute disproportionately to overall IR were also identified. This was done by establishing which linkage chains contribute ≥1% to overall IR (Piet et al., 2015). Management measures targeting such chains can theoretically alleviate the greatest proportion of overall risk to the ecosystem. It should be noted that in addition to IR, the ODEMM approach can also provide an estimate of Total Risk which incorporates scores for the persistence of pressures and the resilience of ecological components to specific pressures (Robinson et al., 2014). However, this estimate is strongly influenced by pressures with long persistence times and/or ecological components with slow generation times and may therefore downplay immediate concerns and management priorities. It is our view and that of others (Pedreschi et al., in review) that this estimate is not appropriate in scoping for immediate management priorities. All analyses were performed through code initially compiled for the ODEMM project, and subsequently modified in its first application outside of the ODEMM project (Pedreschi et al., 2019) and thereafter for use in the Mission Atlantic project. This code is publicly available (https://github.com/gandrat/ODEMM).

Stakeholder engagement

Most of the input data supporting this scoping study were extracted from the most recent NBA 2018 (Sink et al., 2019a). Information gathered for the NBA include published literature (peer-reviewed and grey literature) and were sourced and reviewed to assess functional impact and ecosystem recovery potential for each individual sector across each broad ecosystem group. Data for effort and spatial extent of activities were mapped to provide impact and intensity maps for each sector and sub-sector (e.g. different fisheries) where relevant. Mapping outputs were limited to the EEZ of mainland South Africa (for more detail see Sink et al., 2019a). This assessment is a national collaborative effort greatly reliant on stakeholder inputs. The latest NBA had 478 contributors, 78% of which were external. Contributions were made from public entities (35%), universities (21%), government (21%), private entities (15%) and non-profit organizations (6%), collectively representing 93 institutions in a process that took more than five years to complete (Skowno et al., 2019). As such, the scoring process with stakeholders was not repeated as their views are already captured in the NBA 2018, apart from areas where no local knowledge was available and scores were assigned based on either international evidence or where specific experts were consulted for their opinions. We did, however, present the results of this scoping study to stakeholders during a virtual workshop hosted in November 2021. Stakeholders covering a variety of sectors and pressures, namely agriculture, aggregates (mining), fisheries, aquaculture, pollution, invasive species, non-renewable (oil and gas) and renewable energy, tourism/recreation, and government departments were invited. A total of 24 attendees and 12 different organizations were represented. While greater attendance was anticipated, representation was considered sufficiently broad. Most stakeholders were fully engaged during the workshop and indicated willingness to participate in the ongoing IEA.

The objectives of the stakeholder workshop were (1) to introduce local stakeholders to the IEA methodology and South Africa's role in the Mission Atlantic project, (2) to discuss alignment between the NBA and the IEA, and (3) to discuss immediate priorities and obstacles that hinder EBM implementation in South Africa. Introductions to IEA, the ODEMM approach and South Africa's role in advancing IEA through the Mission Atlantic project were given, after which meaningful discussion of the scoping results provided in this paper was facilitated. Specifically, the top risks to South African marine ecosystems and whether these aligned with stakeholder perceptions were discussed with the aid of online meeting tools such as anonymous polls, followed by carefully facilitated discussion. We did not consider it necessary to perform a rigorous analysis to determine whether stakeholder perception aligned with the outcomes of the scoping study, since most stakeholders in attendance already provided inputs to, or comments on, the NBA. Instead, it was deemed important to discuss whether the top priority actions identified in the latest NBA aligned with the top priorities identified through the scoping study, but this was obviously not an independent test of the framework. These NBA priority actions were identified together with stakeholders in response to key NBA findings, with further consideration of other marine science outputs- and capacity shortcomings. A final discussion was held on important knowledge gaps identified through the scoping and assessment of knowledge confidence levels.

Results

ODEMM risk assessment

The South African assessment included 17 pressures, 17 sectors and 23 ecological components (Figure 1; Supplementary Material Tables 2-4).

Sectors ranked differently based on proportional connectance, mean IR and sum IR (Table 2, Figures 2A, 3A), although fishing consistently ranked the highest in terms of proportional connectance, mean IR and sum IR (Table 2, Figures 2A, 3A). This was followed by shipping and coastal infrastructure (as per sum IR). The mismatch between rankings using sum IR versus mean IR is disconcerting in some cases, for example harvesting/collecting ranked ninth based on sum IR but second based on mean IR, and shipping ranked second for sum IR but only sixth based on mean IR.

As revealed through proportional connectance, most widely distributed pressures in marine ecosystems were: the

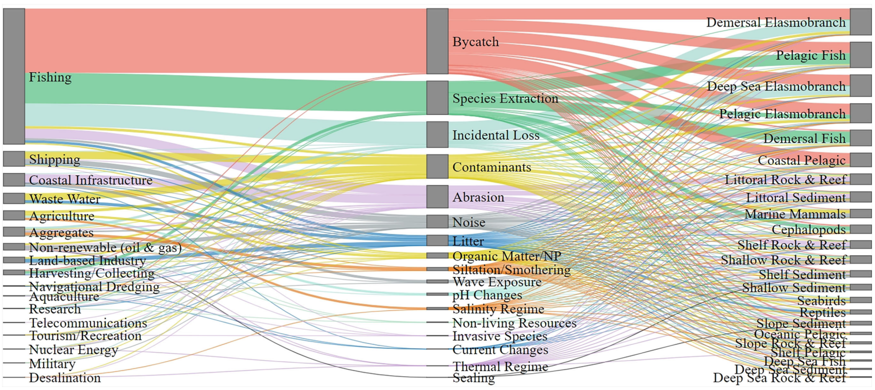

FIGURE 1
South African marine ecosystem risk assessment Sankey diagram illustrating links among sectors (left), their associated pressures (middle) and the ecological components (right) that are impacted by these pressures. The width of the lines represent the Impact Risk (describing the exposure and severity of an interaction). Sectors, pressures and ecological components appear in descending order based on sum Impact Risk scores.

TABLE 2 Proportional connectance, mean impact risk (IR) and rank, and sum IR and rank of South African sectors. Sectors appear in descending order based on sum IR.

Sector	Proportional connectance	Proportional connectance (rank)	IR (mean)	IR rank (mean)	IR (sum)	IR rank (sum)
Fishing	11.65	1	1.22E-01	1	1.24E+01	1
Shipping	10.27	2	1.53E-02	6	1.36E+00	2
Coastal Infrastructure	6.34	7	2.11E-02	4	1.16E+00	3
Waste Water	4.50	12	2.42E-02	3	9.44E-01	4
Agriculture	5.42	9	1.79E-02	5	8.42E-01	5
Aggregates	7.04	6	1.36E-02	7	8.30E-01	6
Non-renewable (oil & gas)	9.11	3	7.70E-03	8	6.08E-01	7
Land-based Industry	8.42	4	7.08E-03	9	5.17E-01	8
Harvesting/Collecting	1.85	16	2.77E-02	2	4.44E-01	9
Navigational Dredging	4.84	11	1.47E-03	12	6.19E-02	10
Aquaculture	2.65	15	1.75E-03	11	4.02E-02	11
Research	7.61	5	5.65E-04	15	3.73E-02	12
Telecommunications	1.15	17	3.12E-03	10	3.12E-02	13
Tourism/Recreation	5.07	10	6.66E-04	14	2.93E-02	14
Nuclear Energy	4.27	13	6.75E-04	13	2.50E-02	15
Military	6.00	8	3.12E-04	16	1.62E-02	16
Desalination	3.81	14	1.80E-04	17	5.93E-03	17

Sectors appear in descending order based on sum IR.

introduction of contaminants, underwater noise, litter, abrasion and organic matter/NP introduction (Figure 3B, Supplementary Material Table 3). The top five pressures as ranked per sum IR were, in descending order: bycatch, species extraction, incidental loss, introduction of contaminants, and abrasion (Figure 2B, Supplementary Material Table 3). Of these pressures, only contaminants did not appear in the top five based on mean IR and was instead replaced by changes in wave exposure (Supplementary Material Table 3).

Ecological components most at risk were: demersal elasmobranchs, pelagic fish, deep sea elasmobranchs, pelagic elasmobranchs, and demersal fish. These were the top five ecological components based both on mean and sum IR, although ranking/order differed (Figure 2C, Supplementary Material Table 6). Interestingly, ecological components with greatest proportional connectance in the framework differed from those based on IR, namely shallow benthic- and littoral habitats (Figure 3C, Supplementary Material Table 6).

Linkage chains that contributed disproportionately to overall IR (i.e. ≥ 1% of the overall IR) were related to two sectors (fishing and coastal infrastructure), four pressures (bycatch, incidental loss, species extraction, abrasion) and affected 10 ecological components; a total of 14 of 868 linkage chains in our framework (Table 3). Of these 14 chains, the greatest contributions stemmed from eight chains, each contributing 5.19% to overall risk and all related to fishing. Collectively, the top-scoring chains explained 54.68% of the IR observed in the ecosystem (Table 3).

Confidence of supporting knowledge

Most links in the framework (51.21%) were supported by a medium level of confidence (i.e. international literature) (Supplementary Material Tables 7-9). This was followed by low confidence (i.e. expert opinion, 30.84% of links) and then by high confidence (i.e. local literature, 17.95% of links). Most linkage chains contributing to the greatest relative IR in the ecosystem (Table 3) were assigned with high knowledge confidence, apart from fishing – bycatch – demersal elasmobranchs/coastal pelagic (supported by international literature, medium confidence) and fishing – incidental loss – deep sea elasmobranchs (supported by expert opinion, low confidence).

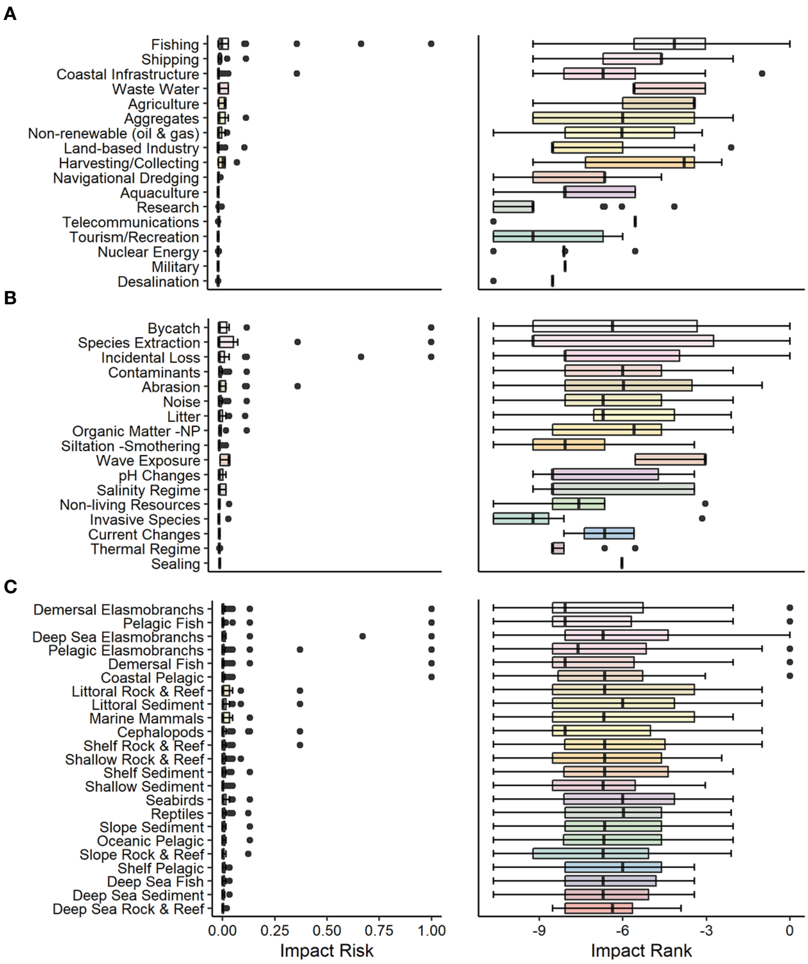

FIGURE 2
Impact Risk and Impact Rank of **(A)** sectors, **(B)** pressures and **(C)** ecological components assessed. Impact Rank values are log-transformed Impact Risk values to allow for better visual comparison among components. Components appear in descending order based on sum Impact Risk. Vertical black lines = medians, box lengths = 25% quartiles, whiskers = 1.5 times interquartile range, outliers = black dots.

Sectors scored with a low knowledge confidence included: telecommunication (i.e. undersea cables; 100% of links), agriculture (97.9%), waste water (56.4%) and aggregates (55.2%). Pressures in which low knowledge confidence dominated included: pH changes (100% of links), input of organic matter/NP (77.6%), litter (56.5%), salinity regime changes (50%) and thermal regime changes (36.8%). For ecological components, marine mammals (42.9%), shelf pelagic habitats (39.3%), reptiles (37.9%), cephalopods (37.8%) and slope sediment habitats (37.5%) had the most links assigned with low knowledge confidence.

Stakeholder engagement

Overall, stakeholders agreed that fishing should rank as the most impactful sector, although the potential bias resulting from greater research efforts in this sector was raised. Low ranking of certain pressures (e.g. invasive species) was also questioned, highlighting the potential influence of research effort bias in assessments. In addition, concerns were expressed that differences in the overall number of species impacted by fishing in shallow (< 50 m) versus deeper (> 50 m) water habitats might not be accurately captured in the current scoring as target species in shallow water habitats are fewer than those in deeper waters (DEFF, 2020). Spatio-temporal mapping of sectors and pressures is needed, and if such maps underpin assessments there may be differences in both time and space in scoring of affected ecological components. While mapping of sectoral activity has been done in the National Biodiversity Assessment (Majiedt et al., 2019), this differs from the classification of sectors and pressures as used in this ODEMM-based study. Mapping actual pressures may provide

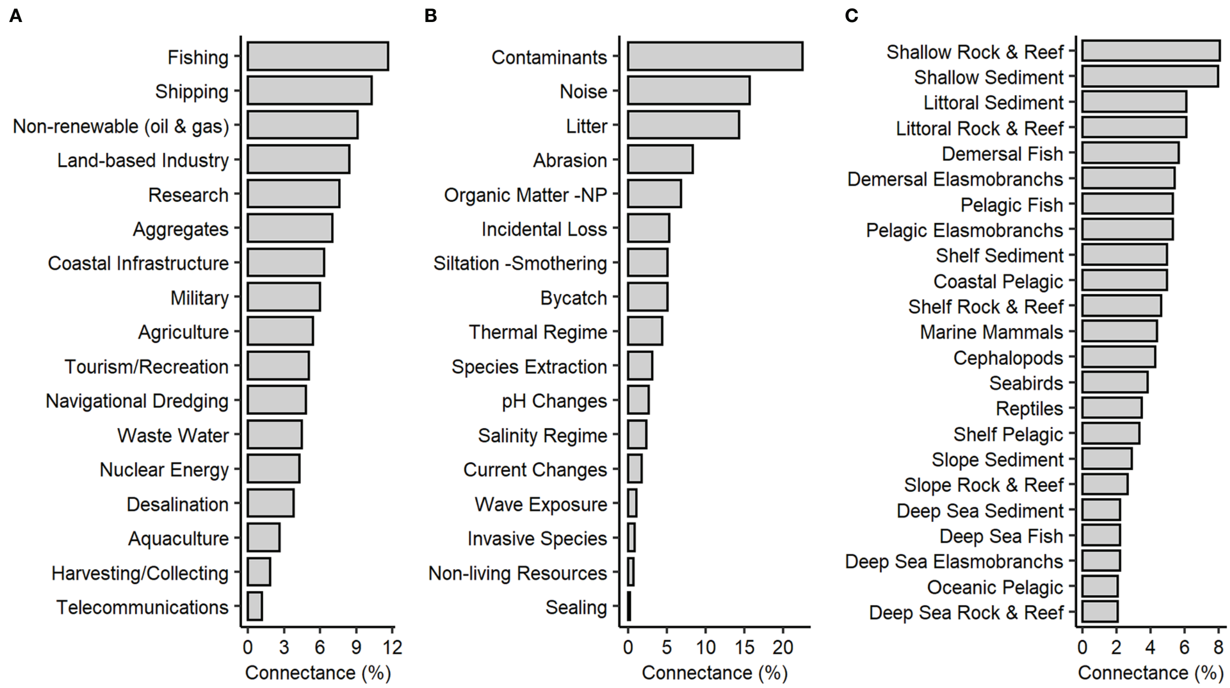

FIGURE 3
Proportional connectance of **(A)** sectors, **(B)** pressures, and **(C)** ecological components in the linkage framework. Based on presence of interactions only and not weighted.

a more accurate picture of where and when sectors are operating and where impacts are likely to be greatest with respect to particular ecological components. The workshop noted that due consideration needed to be given to uncertain present and future impacts from emerging sectors. The need to address key knowledge gaps identified through our assessment on present (e.g. underwater noise, climate change) and future (e.g. offshore renewable energy) pressures was well-supported by stakeholders.

Stakeholders further concluded that the top priority actions defined in the latest NBA remained relevant in light of the major risks identified in this assessment. Support for these priority actions was further confirmed in a discussion on current obstacles to successful EBM implementation. This included the lack of effective fisheries management plans, limited collaboration among different sectors, omission of climate change effects from current spatial assessments and management plans, and shortcomings in Marine Protected Area (MPA) financing and governance that impede their effectiveness. Suggestions to improve the effectiveness of MPAs include the establishment of clearly-defined management targets aligned with the MPA purpose, promotion of MPA data accessibility, increased collaboration among key stakeholders and better alignment of management resources. It was highlighted that NBA-Priority Action 8 – "*Enhancing co-operative governance*" in particular is key for EBM success.

Overall, discussion among stakeholders spanning various sectors and institutions was meaningful and valuable insights were gained. Future engagements should aim to include participants from a broader suite of sectors (e.g. stakeholders from the shipping industry were not represented at our workshop) to ensure that all relevant multi-sectoral and multi-cultural perspectives are accounted for as best possible. It was proposed that future work be directed towards better addressing the vulnerability of South African ecosystem types to pressures such as climate change (not dealt with specifically in the IEA process, see discussion section) and underwater noise (ranked as an important pressure but relatively poorly-researched). A collaborative review of all relevant policy and legislation related to regulation of the South African marine environment was also called for.

Discussion

Key outcomes

The ODEMM approach is useful in providing a holistic picture of all activities taking place in an ecosystem context, and to identify priority thematic areas (and pressures) where management efforts may deliver optimal benefits (Piet et al.,

TABLE 3 Linkage chains with disproportionate contributions (≥1%) to overall Impact Risk (IR).

Sector	Pressure	Ecological component	Relative IR contribution (%)
Fishing	Bycatch	Demersal elasmobranchs	5.198011
Fishing	Bycatch	Pelagic elasmobranchs	5.198011
Fishing	Bycatch	Deep sea elasmobranchs	5.198011
Fishing	Bycatch	Pelagic fish	5.198011
Fishing	Bycatch	Coastal pelagic	5.198011
Fishing	Incidental loss	Demersal elasmobranchs	5.198011
Fishing	Species extraction	Demersal fish	5.198011
Fishing	Species extraction	Pelagic fish	5.198011
Fishing	Incidental loss	Deep sea elasmobranchs	3.482668
Coastal infrastructure	Abrasion	Littoral sediment	1.923264
Coastal infrastructure	Abrasion	Littoral rock & reef	1.923264
Fishing	Abrasion	Shelf rock & reef	1.923264
Fishing	Species extraction	Pelagic elasmobranchs	1.923264
Fishing	Species extraction	Cephalopods	1.923264
TOTAL IR			**54.68%**

2015). Of the many sectors that affect South Africa's marine ecosystems, fishing (and its related pressures) was revealed as the top sector through all ranking metrics used, contributing 64.2% of the overall IR in the assessment. This is understandable, given the wide spatial distribution, continuous operation and severity of some impacts of this sector. Ecological components exposed to the greatest risk were those that are often and severely affected by fishing-related pressures (i.e. fish and elasmobranchs). However, fishing-related pressures are not unique to this sector. For example, pressures such as abrasion, noise and litter are also associated with sectors such as non-renewable energy, coastal infrastructure and shipping, thereby potentially resulting in interactive impacts on ecological components.

Ranking based on mean and sum IR identified similar top sectors, pressures and ecological components, although those identified through sum IR were better aligned with our and stakeholder perceptions. For example, shipping ranked second based on sum IR but only ninth based on mean IR, and was instead replaced by harvesting/collecting that ranked second based on mean IR. Similarly, underwater noise appeared in the top five most impactful pressures based on sum IR, but ranked eighth based on mean IR and was instead replaced with wave exposure changes. The impacts related to shipping and underwater noise can pose greater risks (based on their widespread nature, frequency of occurrence and severity of impacts) in comparison to harvesting/collecting and wave exposure changes. Moreover, when considering the relative IR contribution to the overall framework, these sectors and pressures delivered greater contributions than others ranked higher through mean IR (e.g. shipping = 7.1% vs harvesting/collecting = 2.3%, and noise = 6.1% vs wave exposure changes = 1.5%). Top sectors and pressures as identified through sum IR also feature in all of the most impactful chains (Table 3). A similar pattern was reported by Pedreschi et al. (2019), where the authors suggest that sum IR may be a more appropriate descriptive statistic as opposed to mean IR. For sectors with fewer linkage chains, such as harvesting/collecting, the mean IR scores may overestimate their importance merely as a result of a smaller division, as also highlighted in Pedreschi et al. (2019). We therefore suggest that sum IR may be a better statistic to focus on in future studies using this approach.

A useful aspect of the ODEMM approach was the evaluation of the knowledge confidence supporting scoring of linkage chains. Most of the top scoring links (Table 3) were supported by high knowledge confidence (local literature support). Very little to no research has been done on the impacts of sectors such as agriculture and telecommunication cables on South Africa's marine environment, for example. Other notable gaps in local knowledge include research on pressures such as changes in pH, currents, thermal regimes, wave exposure, and noise. As highlighted in our stakeholder workshop, there is a possibility that greater research effort on some pressures (e.g. bycatch) may bias scoring so that pressures with potentially greater impacts are underestimated, for example underwater noise. Thus, confidence scores help us to identify key areas of potential bias that can be considered when making management decisions based on the results from the ODEMM scoping assessment, and they were important in our context to prioritize new areas of research and pressure mapping, especially where we cannot rely solely on international literature. For a pressure such as underwater noise, impacts are mostly context-dependent and can vary based on local geography (e.g. distance traveled by underwater noise based on ocean floor geography), the hearing ranges of the affected organisms in the specific area, and/or the frequency and intensity of sound produced by different sectors (e.g. shipping/pile driving/seismic airguns) (Popper and Hawkins, 2019; Duarte et al., 2021). For this reason, scores underpinned by international literature may differ from those that would have been supported by local literature, had it been available. This process and the results obtained highlighted the need to further interrogate the outputs, using quantitative approaches, to better understand what proportion of high-scoring pressures or linkages were based on high knowledge confidence, and whether there was a correlation, for example.

Another stakeholder concern regarding the use of the ODEMM framework was the grouping of all fisheries and the possibility that this may further intensify the scores for this sector. However, this approach is recognized as a necessary trade-off so that a broad suite of sectors could be incorporated in the comparative Atlantic ecosystem assessment study of the Mission Atlantic project. A study is currently underway to disaggregate the fishing sectors operating off South Africa to facilitate a gear-specific focus within fishing sectors. In addition, pressures not incorporated into the current ODEMM framework but that likely affect South African marine environments are changes in freshwater flow to marine environments, and pressures associated with sea-based aquaculture such as genetic hybridization and pathogen introduction. These pressures and their potential impacts have been acknowledged in previous ecological risk assessments done for this environment (Sink et al., 2019b) and will need to be examined in more detail in future iterations of the ODEMM assessment.

Although the application of ODEMM in this study has proven useful in supporting the existing (and ongoing) NBA for the South African marine ecosystem as a whole, it has also exposed several limitations and complexities of the method. These include a strong reliance on indicators and classic scientific information that may not adequately capture that of more diverse knowledge systems, and the potential effects of a scoring system that may reflect obvious extremes but may be less accurate in the more nuanced middle ground. For example, the current study is limited in its utility for fisheries management given that all fishing gears are considered together. By contrast, a disaggregated ODEMM wherein fishing sectors are independently assessed could be useful and would further the disaggregated assessment of fisheries in the NBA. IEA-type assessments will be biased towards those sectors (or sub-sectors) for which more research and data are available, possibly underestimating pressures exerted by lesser known/poorly quantified sectors. This is alluded to through assessing the uncertainty of the various pathways and acknowledging those with poor confidence and which require substantially increased research effort. A case in point is pH changes. Firstly, we have low confidence in our estimates of which sectors exert this pressure, and this is compounded by the poor understanding of pH changes across most of our ecological characteristics, with the exception of a few species. It is further noteworthy that important sector-pressure-ecological component pathways may be less quantitatively described (data may be lacking and/or indicators missing) yet may still be high priority pathways for which management actions could be taken based on more qualitative understanding of the issue (e.g. based on local knowledge). As such, it is important to acknowledge the constraints of this approach to IEA, and to recognize that application of multiple IEA-type methods is likely to highlight a range of ecosystem impacts requiring closer attention rather than providing a rigorous and accurate assessment across all sectors. Nevertheless, this study is a valuable contribution particularly when combined with other approaches such as those detailed in the South African NBA (Sink et al., 2019a). Together, these assessments can provide relative priorities to guide improved ecosystem-based management through appropriate and varied management measures. and addressing with appropriate and varied management measures.

Risk assessment approaches for application in the national biodiversity assessment

In the latest NBA (Sink et al., 2019a), the IUCN Red List of Ecosystems (RLE; Rodríguez et al., 2015) approach was applied to assess the threat status of South Africa's marine ecosystem types (Sink et al., 2019b). Given the importance of the NBA and its broad use by decision-makers and scientists, it is useful to draw comparisons between the currently applied IUCN RLE approach and the ODEMM approach so that maximum benefits from the two approaches may be extracted and included in future iterations of the NBA.

Both assessments rely on qualitative scoring, although different input data are required and thus different outputs are produced. Some of the key differences between the recent IUCN RLE and ODEMM approach include that of spatial resolution, the manner in which ecological components are assessed, and the manner in which relationships between different sectors and pressures are assessed. The IUCN RLE requires assessment units that can be clearly spatially delineated and that can assess risks across contrasting ecosystem types. For example, in Sink et al. (2019b), threat status of 150 marine ecosystem types was assessed and it was found that half of these ecosystem types were threatened, amounting to 5% of the national ocean space with greater threats faced by inshore and shelf ecosystem types than by slope and abyssal types. The ODEMM approach does not require high resolution spatial data, although it is possible to perform this assessment at finer spatial scales in order to address specific management questions. In addition, as South Africa's most recent marine ecosystem threat status assessment considered risks for combined bentho-pelagic ecosystem types, it did not distinguish between risks faced by benthic and pelagic organisms but rather grouped them to represent the threat per combined ecosystem type. In ODEMM, benthic and pelagic ecological components are assessed separately and so it is possible to answer different questions regarding the distribution of risk through the two approaches. A strength of the IUCN RLE approach is the spatial pressure mapping component that clearly communicates the distribution of relative risk across ocean space and may thus be valuable in spatial management (e.g. MPA planning). On the other hand, the connectivity aspect of the ODEMM approach (linkage framework) may also provide useful management information, for example by identifying those areas where improved regulation will achieve the optimal risk reduction for the ecosystem as a whole, or for particular high-priority ecological components. As such, it is our view that the outputs of the two approaches can be complimentary and tailored to answer specific research and management questions.

Future priorities

The present study identified top pressures and sectors that represent management and research priorities. Following the IEA cycle, the next stages are indicator development and more semi-quantitative and quantitative risk analyses. Development of meaningful ecological indicators, linked to identified ecological components, can help to identify drivers of change, quantify pressure-state relationships and determine ecological tipping points and thresholds. Such indicators can be used to measure the state or condition of marine ecosystems (Levin et al., 2009; Tallis et al., 2010; Knights et al., 2011) including ecosystem threat assessments using the IUCN methodology, and can help evaluate the effectiveness of management interventions (Levin et al., 2009; Samhouri et al., 2012). Initial steps have been taken in South Africa to identify key challenges that hinder national marine ecosystem assessment, where recommendations and tangible priority actions have been identified to overcome these challenges (Smit et al., 2022). Work is underway to advance marine ecosystem assessment and to further develop an indicator and assessment framework where ecological indicators will also support upcoming semi-quantitative and later quantitative risk assessments (Keith et al., 2013; Skern-Mauritzen et al., 2018; Smit et al., 2021).

Climate change was not included as a pressure in this study. This is because it will likely be connected to most (if not all) ecological components, and because its impacts are complex and interactive, and not as well understood as that of other pressures included in this assessment. As such, including climate change in this assessment may likely have obscured other meaningful patterns that were otherwise revealed. However, upcoming semi-quantitative and quantitative assessments that will focus on areas of management priority (such as those identified in this study) will account for the potential effects of climate change, where data availability allows. Addressing knowledge gaps related to the interactive effects of climate change and other top pressures will thus be key in advancing our ability to better account for climate change in EBM-orientated management plans.

The consideration of climate change impacts in spatial assessments was highlighted by our stakeholders, and could be guided by focused ecosystem model simulations, for example (Ortega-Cisneros et al., 2018). Lastly, there is a need to synthesize all relevant policy pertaining to pressures in South Africa's marine ecosystems. Taljaard et al. (2019) provide an overview for coastal habitats, and Ortega-Cisneros et al. (2021) reviewed the country's potential to address climate change impacts in its fisheries, but these studies need to be extended to include all pressures across the entire national ocean space. This will be important not only for communication purposes with decision-makers, but is also a key step in streamlining management objectives to better incorporate EBM principles, and implementing management actions that best address ecosystem risks.

Conclusion

It is our view that the application of the ODEMM approach in the South African case study provides added value beyond what is already known and documented in terms of pressures exerted by the various ocean users/sectors. However, we also note that this approach should not be interpreted as fully comprehensive, given its inability to capture understudied components, distinguish between some sub-sectors (e.g. fisheries), or accounting for diverse knowledge use systems that may not be easy quantifiable in scientific terms. Rather, the value of this approach lies in summarizing stakeholder and expert knowledge in a logical and coherent manner, and combining this into a product from which further research and improved stakeholder collaboration is encouraged with an ultimate goal of achieving more sustainable human interactions with our marine ecosystem.

The interconnectedness of human sectors and their respective pressures on marine ecological components is clearly demonstrated in this study. With fishing revealed as the most impactful sector, the importance of improving fisheries management plans, while accounting for interactive effects of pressures originating from other sectors, is imperative. Alongside an accumulating body of work, this research emphasizes the need to transition toward EBM in South Africa and globally. The tools to support EBM have become more sophisticated and adaptable, providing outputs that can meaningfully support management. It is our view that IEA represents one such tool, and the work presented here is the first step toward better management of most impactful human activities in our marine systems. Intact marine ecosystems that are resilient to future change while still supporting human needs strongly depend on the success of such management.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Author contributions

This work was coordinated by LJS who leads the South African case-study in the MISSION ATLANTIC project. LS led the writing of the manuscript, performed the analyses and coordinated the stakeholder workshop, in which all authors contributed scientific and logistical support. The majority of initial scoring was performed by MB, KJS and PAM and later refined by LS. All authors contributed to the writing of the manuscript and approved the submitted version.

Funding

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 862428 (MISSION ATLANTIC). This output reflects only the author's view and the Research Executive Agency (REA) cannot be held responsible for any use that may be made of the information contained therein.

Acknowledgments

LS, LJS and KPS were funded by MISSION ATLANTIC and data analyses were conducted as part of MISSION ATLANTIC Horizon 2020 Research and Innovation Program (862428). We thank Debbi Pedreschi and David Reid for meaningful guidance on the ODEMM framework. We would also like to express gratitude toward all the stakeholders that attended our workshop on 21 November 2021 and the co-investigators, collaborators and stakeholders who participated in the 2018 National Biodiversity Assessment. KJS acknowledges the Deep Connection project (National Research Foundation Grant 129216).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2022.975328/full#supplementary-material

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