Developing and applying indicators to support marine ecosystem assessments

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Objective – A briefing note aims to provide a concise outcome-based synopsis of recent research or expert opinion that may inform decision making and activities by authorities, NGOs and NPOs. The briefing note series complements the academic peer reviewed literature published by SAIAB.

Objective**:** This technical brief provides an outcome-based synthesis of current research on ecological indicators for assessing the condition of marine ecosystems. It draws primarily from the review by Smit et al. (2021), which consolidated global approaches to indicator selection, and builds on subsequent work in South Africa that tested the performance of potential indicators from rocky reef ecosystems (Smit et al. 2023). The brief highlights the importance of defining ecological condition, explains the framework and types of indicators to assess condition and demonstrates the use of benthic (invertebrates growing on the reef)- and fish-based indicators as a case study.

Background

Deciding what biological characteristics to measure in marine ecosystems is extremely difficult. As yet, we don't fully understand the functioning of marine ecosystems as a whole, including their natural states, how they are changing and what is driving these changes. However, past research has identified numerous characteristics of marine ecosystems that are indicative of the ecosystem health and functioning and respond predictably to environmental and anthropogenic pressures. These indicators help us to understand how our oceans are changing and whether our efforts to manage and protect them are working. They turn diverse scientific observations into clear measures that can show if marine ecosystems are healthy, under pressure, or improving, helping managers and policymakers take action based on evidence.

Indicators can be defined in various ways, depending on the end goal and who is using the information that they convey. But generally, in a marine context, they are defined as a tool "to monitor and assess the state of the marine environment and to manage human activities having an impact upon it" (European Commission, 2008b). More specifically, Smit et al. (2023) defined an indicator as any measurable ecosystem attribute that responds to pressures (natural or anthropogenic) acting on an ecosystem and that can be used to monitor the trends in the state or condition of marine ecosystems. However, it is difficult to identify the most suitable indicators that depict ecologically meaningful change and are suitable to inform management decisions. This is particularly difficult in the marine realm, where large parts of the ocean are inaccessible and our knowledge on ecosystem functioning and processes is poor. This challenge often results in new indicators being developed and promoted; leading to the proliferation of alternative indicators, without clear guidance on their selection and applicability. Furthermore, most ecological or biodiversity indicators are developed for scientific purposes, and often fail to address management and decision-making processes or inform policy development. This defeats the fundamental purpose an indicator - to provide practical tools that bridge science, management, and policy.

South Africa is relatively advanced among developing countries, with regular National Biodiversity Assessments (NBA) and a history of innovative monitoring approaches. Yet, structured frameworks for selecting and applying marine indicators to measure ecosystem condition remain limited. Such measurements are important in groundtruthing and calibrating assessments from local to national scales. This brief builds on a trajectory of research at SAIAB, SANBI and partner institutions to address this gap.

Indicator selection

Indicators need to be fit-for purpose, and their selection should be guided by a set of criteria. Important criteria to consider include the ability to capture ecosystem condition accurately, sensitivity and robustness to detecting change, discrete responses to natural and anthropogenic drivers of change, transferability across spatial and temporal scales, cost effectiveness, ease of use and the ability to communicate accurate and relevant information to management (Table 1).

Indicators of ecosystem condition can range from simple, single-species population parameters to more complex, trophic models and indicators of ecosystem resilience (Hayes et al., 2015; Rice, 2003; Rombouts et al., 2013). While simple indicators are easy to measure, their response to a particular stressor may not always reflect the response of an assemblage or other components of the ecosystem to that stressor (Probst and Lynam, 2016; Ruaro et al., 2020). On the other hand, indicators that capture multiple attributes of an ecosystem are harder to measure, but may be more robust and sensitive to fluctuations in ecosystem condition (Borja et al., 2009a). Therefore, it is often necessary to use a combination of multiple and contrasting indicators to understand the condition of the ecosystem as a whole (Rombouts et al., 2013). However, a balance must be found between the amount of data needed to calculate relevant indicators, and the time and resources required to do so.

Table 1. Common criteria used for selecting, testing and applying indicators of ecosystem condition (Hayes et al., 2015; Mcfield and Kramer, 2007; Rice, 2003; Rice and Rochet, 2003)

Criterion	Description of indicator
Sensitive	Is able to provide early warnings and early detection and accurately reflects the condition of the environment.
Representative and transferable	Can be broadly applied at different spatial and temporal scales, across regions and potentially across different habitat types.
Responsive	Is able to establish priorities for management and inform decision-making in a reasonable time.
Ecologically meaningful	Is able to be understood and interpreted and can distinguish between natural and anthropogenic drivers of change, by incorporating sound ecological theory.
Measurable	Should provide the necessary tools and methods for measurement, and its effectiveness should be relatively independent of sample size.
Easy and cost-effective	Is easy to use and interpret and data collection costs should be minimised.
Able to set reference points	Should include the necessary data and methods to set baselines and establish thresholds for conservation purposes.
Able to create awareness	Should aim to improve environmental understanding and awareness to engage effectively with various stakeholders.

A first step in selecting indicators is to define what constitutes "good" versus "poor" condition, or, more broadly, to identify the key "values" of the ecosystem. Hayes et al. (2015) suggest starting with two guiding questions: (a) what do we value in an ecosystem, and (b) why do we want to monitor it? We often measure condition in relation to a reference state or baseline, typically measured through its biodiversity structure (e.g., species composition and abundance) and functioning (e.g., trophic dynamics and productivity). In marine systems, truly pristine baselines are rare or unknown, making it difficult to establish clear reference states. In such cases, well-designed and effectively managed marine protected areas (MPAs) can serve as important reference conditions, representing near-natural or minimally impacted examples of the ecosystem. Defining these reference conditions provides the foundation against which trends in indicators can be interpreted, allowing managers and scientists to distinguish between natural variability and human-induced change, and to evaluate whether ecosystem condition is stable, declining, or improving.

A review by Smit et al (2021) identified five categories of indicators used in marine ecosystem assessments, either collected *in-situ* (measurements taken directly from the marine environment, e.g., field surveys), or ex-situ (derived externally from secondary data or models – outside of the field environment), and varying on a continuum of level of inference of ecosystem state, and the amount of ecological data required to inform the indicators (i.e., monitoring requirements)(Table 2). These include:

1. Pressure indicators – capture drivers such as fishing effort, pollution, or coastal development.
2. Physical indicators – measure abiotic factors (temperature, sedimentation, oxygen).
3. Structural indicators – describe biological community composition (species richness, abundance).
4. Functional indicators – reflect ecosystem functioning (size spectra, trophic structure, productivity).
5. Ecological models – integrated indices combining multiple metrics (e.g. Ocean Health Index).

Table 2. Conceptualisation of indicator categories and types of measurements that can be used to measure ecosystem condition. This framework is built around our definition of ecosystem condition and considers the capacity of indicators to directly measure the structure and functioning of the ecosystem, relative to a reference condition. Indicators that include structure and functioning are considered as direct measurements of ecosystem condition, whereas those that include only one aspect of the ecosystem (human pressures or physical at- tributes) are considered an indirect measurement. Indicators can comprise ex situ measurements, which include condition drivers that act on the ecosystem (e.g. pressures). Alternatively, in situ indicators incorporate measurements of ecological at- tributes from within the ecosystem. There are trade-offs as indicators become more direct measurements of condition, including monitoring (and ecological data) requirements which increases from low to high, but the level of inference tends to decrease.

Complexity/int

Indicator categories	Type of measurement		Example	
Pressures	Ex situ	Indirect	Cumulative impact scores	Level of inference
Physical parameters	In situ		Nutrient concentration	
Biological structure			Species composition	
Functional structure		Direct	Functional diversity	Ecological data require-ments
Food webs/ecosystem models			Total system throughput	

Source: Smit et al. (2021)

What do we use these indicators for and who needs them?

Indicators have a wide range of end-uses, serving different purposes across scientific, management, and policy contexts. They can inform everything from local site-based decision-making to international reporting and global observation initiatives. At the management level, indicators are used by MPA managers and resource managers to support long-term ecological monitoring, assess MPA effectiveness, guide zoning, and inform adaptive management. They can also be applied in specific research contexts, including targeted ecological studies or student projects that address particular management or scientific questions.

In South Africa, ecological and biodiversity indicators contribute directly to national assessments and reporting frameworks, such as the National Biodiversity Assessment (NBA) - where Ecosystem Condition is a key headline indicator - and State of the Environment - reports produced by government departments and local management authorities. Regionally, indicators feed into initiatives such as the Western Indian Ocean (WIO) State of the Ocean Report, while globally, they support programmes like the Global Ocean Observing System (GOOS) BioEco framework, and the development of Essential Ocean Variables (EOVs) and Essential Biodiversity Variables (EBVs) from the Group on Earth Observations Biodiversity Observation Network (GEO BON). Further, indicators are important for reporting under the Convention on Biological Diversity (CBD), of which South Africa is a signatory. It is therefore important to consider existing reporting needs and initiatives when developing or applying indicators, ensuring that data are channelled through appropriate mechanisms and that indicators are designed to be meaningful and useful across multiple scales—from site-level management to national, regional, and global reporting.

Given the wide range of possible applications, it is essential to have clear processes and frameworks to guide the selection and use of indicators. Rather than focusing on developing a universal set of indicators, it is more important to establish transparent and repeatable steps for identifying indicators that are most relevant to a particular context. There is no one-size-fits-all approach - indicator choice will always depend on the ecosystem type, pressures, environmental conditions, and management or research objectives. However, it is still possible to do this while adhering to the criteria listed in Table 1. For example, if the goal is to track long-term ecosystem trends, broader biodiversity indicators such as total abundance, species richness, or diversity may be most suitable. In contrast, ecosystem condition assessments require indicators that clearly distinguish between good and degraded states, supported by an understanding of how indicators respond to local pressures, and the definition of reference conditions and thresholds to evaluate current status.

Recognising these complexities, Smit et al. (2021) proposed a structured framework to guide indicator selection and application across marine ecosystems. This framework emphasises the process of identifying, testing, and validating indicators - ensuring they are relevant, scalable, and aligned with existing national and regional programmes such as the NBA, CBD reporting and globally recognised EBVs. By focusing on the process rather than a fixed set of indicators, this approach promotes standardisation, comparability, and effective uptake of indicators within and across management and reporting frameworks (Figure 1).

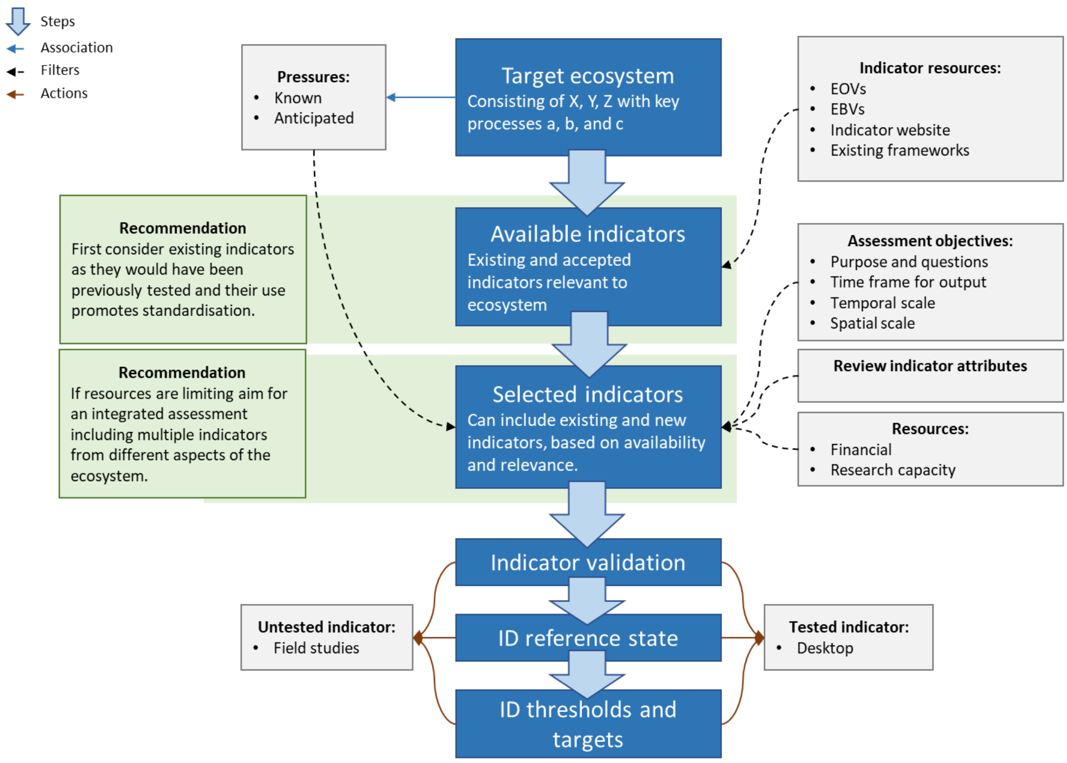

Figure 1. Conceptual framework to guide indicator selection. The main steps are shown in blue boxes with specific associations, filters and actions required throughout the multi-step process. In most instances, target ecosystems will be associated with an existing body of knowledge for its structure and functioning and pressures. Various resources can be used to filter the available indicators down to a manageable final set. A pilot study, either via a desktop review or field surveys, is recommended to validate indicators and establish baselines and targets. Steps not shown include sampling methods which should be guided by internationally standardised protocols and endorsed best practices. Source: Smit et al. (2021).

From framework development to implementation: A South African case study

Building on the indicator selection framework developed by Smit et al. (2021), our subsequent research applied the process to a target ecosystem, rocky reefs and adjacent demersal habitats, in South Africa (see Figure 2 below for the study area) to test and refine how indicators can be used to measure ecosystem condition in practice. The first step was to identify and characterise reference conditions that represent good ecological state. Because historical baselines are rarely available, we used well-protected and effectively managed MPAs such as Tsitsikamma National Park and Pondoland (Figure 2) as proxies for near-natural reference systems. These provided a benchmark against which to compare reefs exposed to varying human pressures. Using Baited Remote Underwater Stereo-Video Systems (Stereo-BRUVs) and benthic ("bottom") imagery data, we tested a range of compositional, functional, and size-based metrics to identify which indicators were most responsive and sensitive to gradients of human pressure.

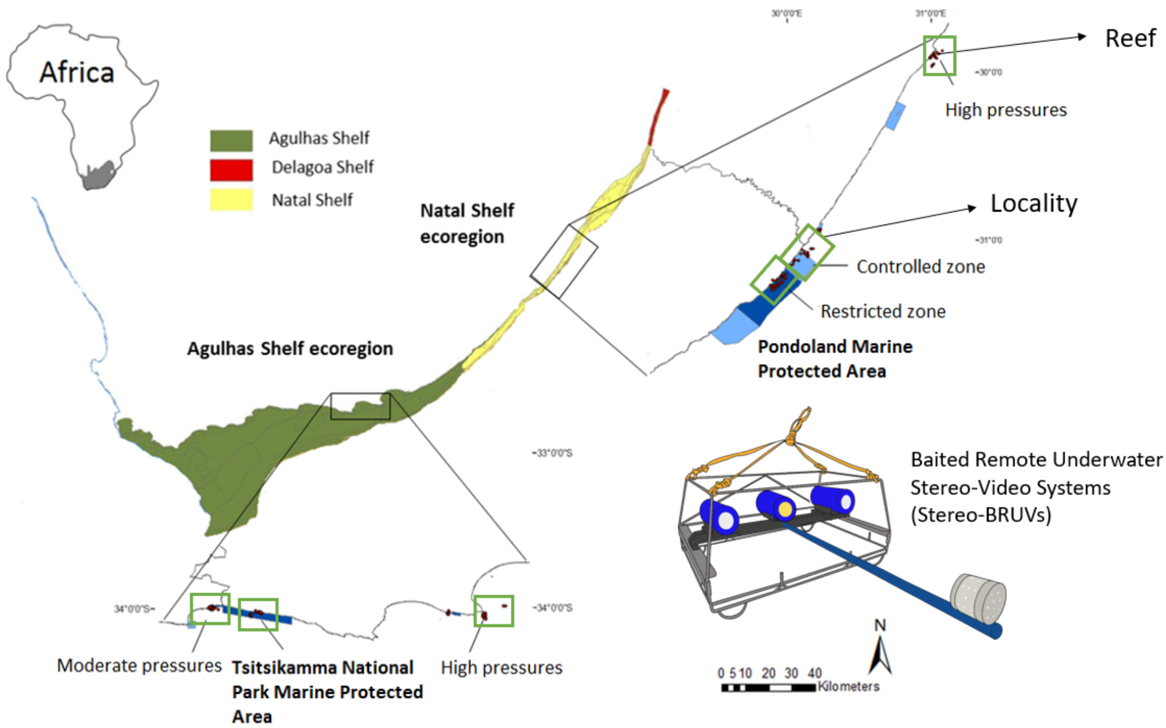

Figure 2. Study area showing the sampling localities (green squares) in the Agulhas Shelf and Natal Shelf ecoregions. Deployment sites are shown in red in each Locality and marine protected areas are shaded in blue (light blue = controlled zone, dark blue = restricted zone). Source: Smit et al., 2023.

What did we learn?

Results showed that traditional structural metrics such as total abundance and species richness were less effective at distinguishing ecosystem condition than size-based and functional indicators. Metrics such as total biomass, mean length, and the proportion of mature or large-bodied fish were more sensitive to differences between well-protected and impacted sites (Figure 3). In systems under higher anthropogenic pressure, fish communities tended to have a greater abundance of small, low-trophic-level species and fewer predators or large individuals, while benthic assemblages were dominated by turf algae and showed a loss of structural complexity. In contrast, sites in good condition supported higher biomass of target species (fisheries-important species), a greater proportion of predators, and structurally complex benthic habitats dominated by upright and branching morphologies ("structural forms"). These results provide a clear quantitative and visual basis for distinguishing "good" versus "poor" ecological condition, demonstrating the utility of size-based, trait-based, and functional indicators for assessing the response of reef ecosystems to human pressures.

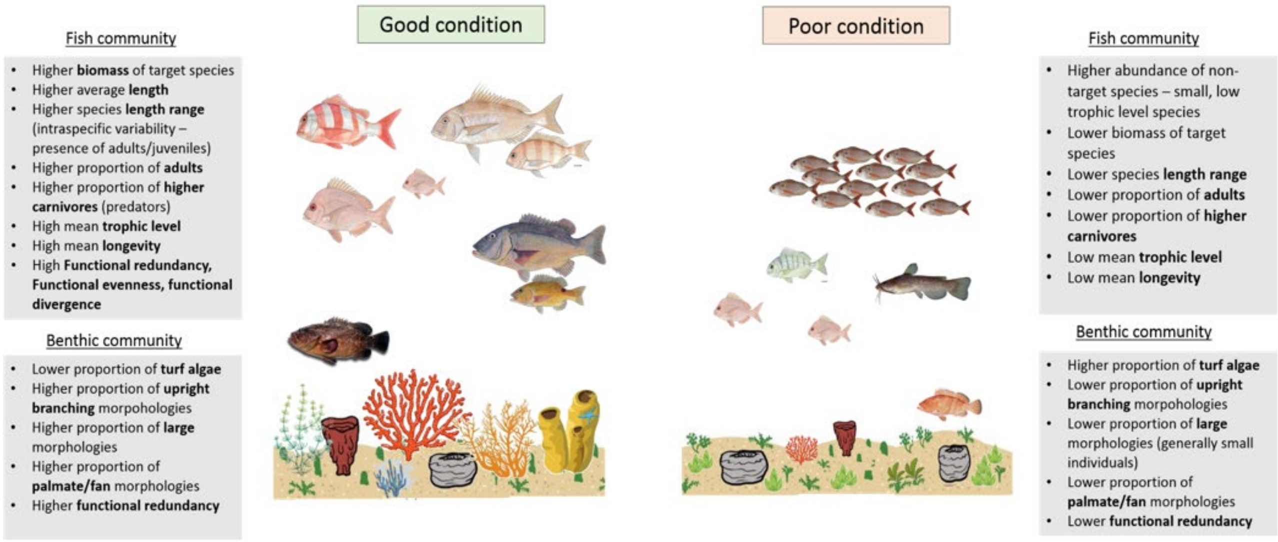

Figure 3. Defining reference conditions - characteristics of good and poor ecological condition of rocky reefs using selected fish and benthic indicators that were sensitive to human pressures and were able distinguish between sites with low and high cumulative pressures/ impacts (Smit, 2020). Relevant indicators and their characteristics are shown in the grey boxes.

Building on these findings, Smit et al. (2024) applied the proposed indicators in an integrated ecosystem assessment, testing how empirical in situ condition measurements compared with modelled cumulative impact assessments used in South Africa's National Biodiversity Assessment (NBA) (Sink et al., 2019). Using fish and benthic data collected across pressure gradients, we applied methods from the HELCOM BEAT and NEAT (Nygård et al., 2018) tools to derive empirical condition scores and categories and compared them to the NBA's pressure-based "modelled condition" categories. This groundtruthing exercise showed that aggregated fish indicators were generally more sensitive to human pressures than benthic indicators and that in situ condition results revealed local-scale variability that broad-scale cumulative models often failed to detect. However, correlations between pressure-based condition indices and those derived from in situ ecological data showed that cumulative impact assessments are still valuable for national scale assessments where ecological data are lacking.

Condition scores were then "graded" using thresholds applied in the NBA to determine the overall condition status, ranging from Natural/Near-natural to Very severely modified (Figure 4). At the extremes, very low or high cumulative impacts, we observed the most correspondence with ecological condition. At all other locations, there appeared to be more sites in poorer condition than estimated by pressure mapping. However, this was not consistent, with the opposite being true at a few sites.

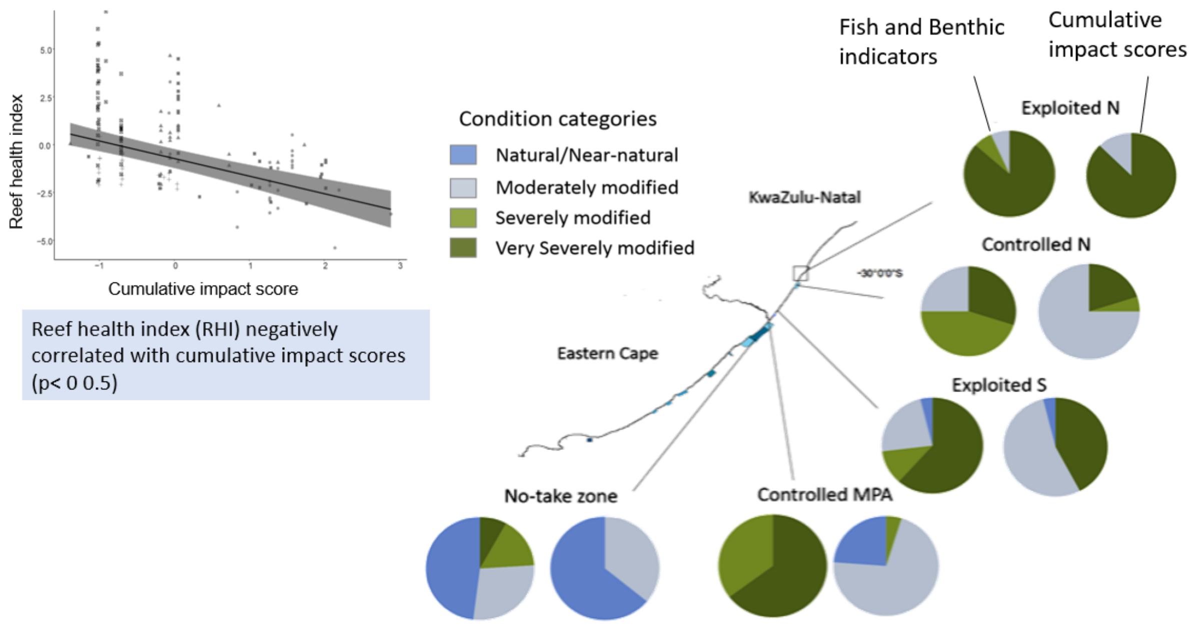

Figure 4. Groundtruthing national pressure-based assessments for the National Biodiversity Assessment (NBA). A correlation between the integrated reef health index, based on in situ ecological data, and the cumulative impact scores from the NBA showed a significant relationship at $p<0.05$, but with high site-level variability. Condition scores were then graded using thresholds from the NBA, to determine condition categories and the proportion of these at each locality, comparing those using fish and benthic indicators with those from cumulative impact scores. Source (Smit, 2020).

Conclusion

Our research has progressively advanced from conceptual development to applied implementation of marine ecosystem indicators with important implications for biodiversity assessment. Starting with the Smit et al. (2021) framework, which outlined a structured process for selecting and applying indicators, we applied this approach to rocky reef ecosystems to identify suitable metrics and define ecological condition using data from well-protected MPAs as reference sites (Smit et al., 2023). In the final stage, we tested and validated these indicators to groundtruth national cumulative impact assessments and strengthen ecosystem condition assessments for the National Biodiversity Assessment and other reporting obligations (Smit et al., 2024). Some key insights included:

- Large, well-designed and well-managed MPAs are effective at maintaining good ecological condition. These MPAs can therefore serve as useful reference states.
- Areas of high cumulative pressures are reflected in the loss of key functional groups and signs of ecosystem degradation
- We need to improve condition in some MPAs, particularly the smaller ones; however, further investigation is required to identify appropriate mitigation measures and key sites.

Together, these studies form a cohesive pathway from framework development to real-world application, linking scientific indicators with national and regional reporting needs. This trajectory has strengthened the empirical basis for assessing ecosystem condition in South Africa and contributed towards the refinement of pressure-based assessments used in the NBA and for future reporting. Recommendations for future research include expanding this approach to other areas, ecosystem types and functional groups. Further we must continue to test and validate indicators and thresholds used for condition assessments.

References

Hayes, K.R., Dambacher, J.M., Hosack, G.R., Bax, N.J., Dunstan, P.K., Fulton, E.A., Thompson, P.A., Hartog, J.R., Hobday, A.J., Bradford, R., Foster, S.D., Hedge, P., Smith, D.C., Marshall, C.J., 2015. Identifying indicators and essential variables for marine ecosystems. Ecol. Indic. 57, 409–419. https://doi.org/10.1016/j.ecolind.2015.05.006

Mcfield, M., Kramer, P., 2007. Healthy Reefs for Healthy People: A Guide to Indicators of Reef Health and Social Well-being in the Mesoamerican Reef Region. With contrbutions by M. Gorrez M. McPherson 208pp.

Nygård, H., Murray, C., Andersen, J.H., Martin, G., Torn, K., Korpinen, S., 2018. BEAT 3.0 – a Tool for Integrated Biodiversity Assessments. J. Open Res. Softw. 6, 1–5. https://doi.org/10.5334/jors.226

Probst, W.N., Lynam, C.P., 2016. Integrated assessment results depend on aggregation method and framework structure – A case study within the European Marine Strategy Framework Directive. Ecol. Indic. 61, 871–881. https://doi.org/10.1016/j.ecolind.2015.10.040

Rice, J., 2003. Environmental health indicators. Ocean Coast. Manag. 46, 235–259. https://doi.org/10.1016/S0964-5691(03)00006-1

Rice, J.C., Rochet, M.J., 2003. A framework for selecting a suite of indicators for fisheries management. Ocean Coast. Manag. 46, 235–259. https://doi.org/10.1016/j.icesjms.2005.01.003

Rombouts, I., Beaugrand, G., Artigas, L.F., Dauvin, J.-C., Gevaert, F., Goberville, E., Kopp, D., Lefebvre, S., Luczak, C., Spilmont, N., Travers-Trolet, M., Villanueva, M.C., Kirby, R.R., 2013. Evaluating marine ecosystem health: Case studies of indicators using direct observations and modelling methods. Ecol. Indic. 24, 353–365. https://doi.org/10.1016/j.ecolind.2012.07.001

Ruaro, R., Gubiani, É.A., Hughes, R.M., Mormul, R.P., 2020. Global trends and challenges in multimetric indices of biological condition. Ecol. Indic. 110, 105862. https://doi.org/10.1016/j.ecolind.2019.105862

Sink, K., van der Bank, M., Majiedt, P., Harris, L., Atkinson, L., Kirkman, S., Karenyi, N. (eds), 2019. South African National Biodiversity Assessment 2018 Technical Report Volume 4: Marine Realm. Pretoria, South Africa.

Smit, K.P., 2020. A trait-based approach to identify indicators to measure ecosystem condition of rocky reefs in South Africa (Doctoral disssertation). (Doctoral Diss. Nelson Mandela University, South Africa.

Smit, K.P., Bernard, A.T.F., Lombard, A.T., Sink, K.J., 2021. Assessing marine ecosystem condition: A review to support indicator choice and framework development. Ecol. Indic. 121, 107148. https://doi.org/10.1016/j.ecolind.2020.107148

Smit, K.P., Bernard, A.T.F., Sink, K.J., Dyer, A., Lombard, A.T., 2023. Identifying suitable indicators to measure and define ecological condition of rocky reef ecosystems in South Africa. Ecol. Indic. (Accepted.

Smit, K.P., Sink, K.J., Shannon, L.J., Bernard, A.T.F., Lombard, A.T., 2024. Groundtruthing cumulative impact assessments with biodiversity data: Testing indicators and methods for marine ecosystem condition assessments in South Africa. Aquat. Conserv. Mar. Freshw. Ecosyst. 34, 1–19. https://doi.org/10.1002/aqc.4096

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