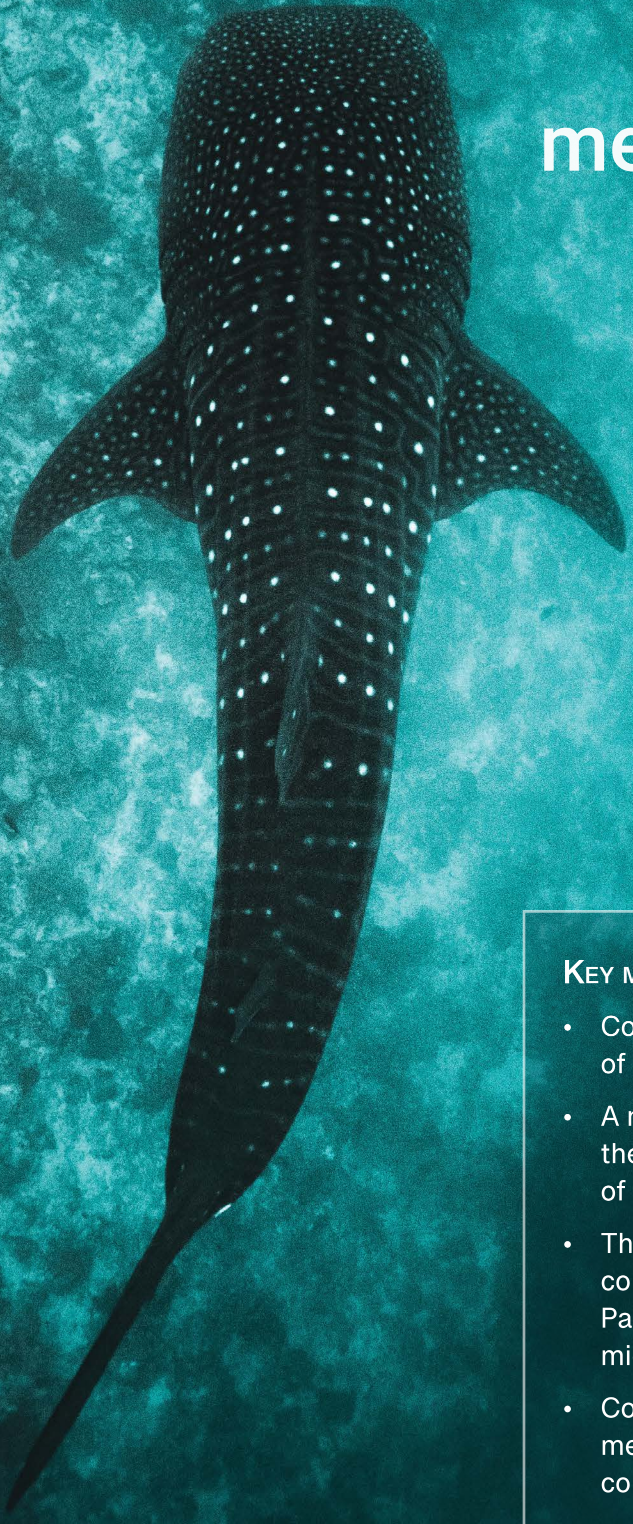
POLICY BRIEF

Linking distant worlds:

Understanding and measuring connectivity in the global ocean

D.C. Dunn, L.K. Bentley, A-L. Harrison & A. Metaxas



Key messages

- Connectivity is critical to delivering on the goals and targets of the Kunming-Montreal Global Biodiversity Framework.
- A new study and online tool (the Migratory Connectivity in the Ocean system, MiCO) provide the first global snapshot of marine migratory connectivity.
- The MiCO system allows Parties to assess known connectivity of migratory species that use their EEZ, and Parties with which they share responsibility for managing migratory marine populations.
- Connectivity in the marine realm is better addressed by measures of functional connectivity, not the structural connectivity measures that are used in terrestrial areas.
- Connectivity metrics exist for the marine realm and for migratory species and these should be prioritised for inclusion the the GBF monitoring framework.

What is connectivity?

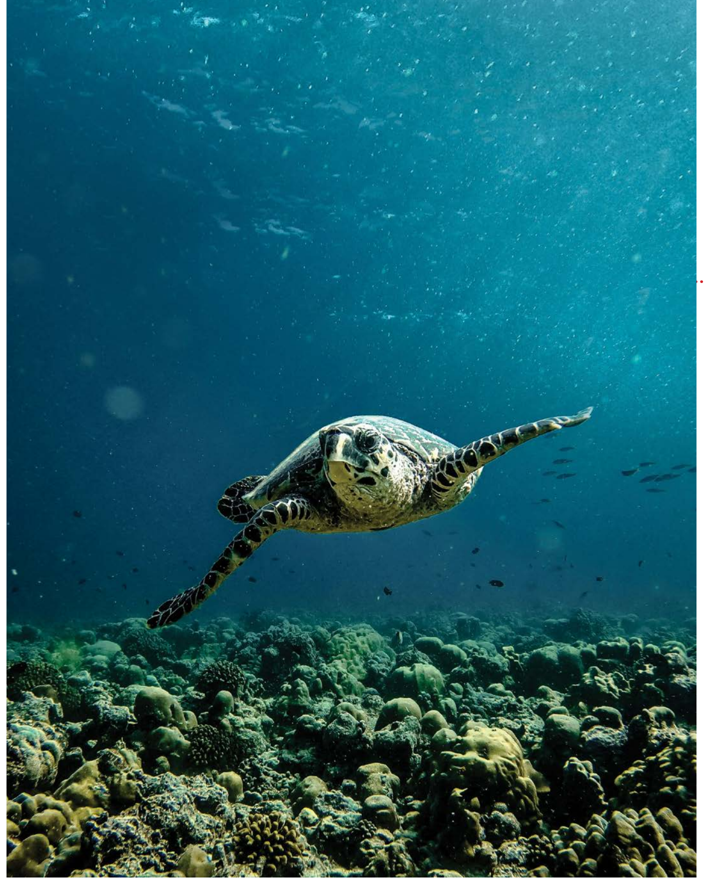
Whether it is the transport of microscopic coral larvae via ocean currents or the migration of a blue whale, the world's largest animal, ecological connectivity simply describes the flow of matter or energy from one place to another. Global ecosystem health depends on this movement of nutrients, propagules and individuals, but these links between worlds are increasingly under threat. The global biodiversity crisis has seen migratory journeys disrupted, ocean currents changed, and even when populations remain connected, diseases and invasive species often travel the same paths between systems. The Kunming-Montreal Global Biodiversity Framework (GBF) recognises the importance of ecological connectivity to deliver critical societal goals for the conservation and sustainable use of biodiversity. This brief seeks to explain what ecological connectivity is through the lens of marine and migratory species, why it is important, how it is measured, and how marine and migratory connectivity indicators can be incorporated in the GBF.

Why is connectivity important?

Healthy populations require functional connectivity for key processes, including dispersal of larvae or juveniles, important nutrient cycling, and maintenance of genetic diversity. Fragmented landscapes or changes to connectivity in marine environments (for example, loss of source populations or changes in oceanographic flow) limit these exchanges, weakening ecological functions and making populations more vulnerable to environmental stressors. As the planet warms, the capacity for biodiversity to move polewards depends on the maintenance of connectivity across suitable habitats. Further to this, the capacity of recruits to successfully move between source and sink populations is critical for population health. In turn, this is ultimately linked to the health of entire ecosystems, and their continued ability to provide the provisioning, regulating, and cultural services upon which humans rely.

GBF Goal A aspires that "the integrity, connectivity and resilience of all ecosystems are maintained, enhanced, or restored, substantially increasing the area of natural ecosystems by 2050". Connectivity is also explicitly stated as part of Targets 2, 3 and 12, and is indirectly related to elements of Targets 5 and 6. In the context of the GBF, the underlying role of connectivity in meeting Goal A is relatively tangible: it is expected to contribute to an increase in the area of different ecosystems, reduce species' extinction rates or risk, enhance genetic diversity and contribute to the resilience of wild species.

However, Targets 2, 3, and 12 aspire to "enhanced" connectivity without providing a reference or context that can be used to derive quantitative objectives. Moreover, decisions on the types of connectivity to use and appropriate targets for connectivity are not straightforward, and can require knowledge that may not exist or even be attainable. An added complexity is introduced by certain fundamental differences in aspects of connectivity between the terrestrial and marine realms.



How is connectivity measured?

There are typically two ways of categorizing connectivity, and each is measured differently. The first type, **structural** or landscape/seascape connectivity, focuses on the physical characteristics of habitats and their arrangement. The second type, **functional** connectivity, emphasises the flow of individuals, species, energy, or materials, and the outcome of that movement (such as population growth and/or species persistence). The type of connectivity that should be considered depends on the species, realm and conservation goals.

Overall, the great dispersal potential of many marine species means that places and populations are connected over larger spatial scales in the ocean than on land. Because movement in the ocean is not constrained by the presence of continuous suitable habitat (as most species have a larval phase allowing dispersal through the water column), structural connectivity becomes a poor proxy for functional connectivity. Subsequently, more focus is placed on metrics of functional connectivity, such as: (i) measuring the transport of propagules and understanding the factors that aid or hinder this transport, and (ii) determining the appropriate size of a management area to ensure larvae or juveniles are retained and settle. For migratory connectivity, the emphasis is on the connections between key sites in animals' life cycles, such as between breeding and post-breeding areas, and how a population remains separated or intermingles during their migrations.

Connectivity indicators for marine systems

Various methods are employed to measure connectivity for networks of populations, habitats, ecosystems or protected areas in coastal and marine ecosystems. These metrics focus on estimating the strength and magnitude of connections in order to assess, for example, the contribution of larval connectivity to population viability, or the importance of particular places in a protected area network. In particular, there are seven connectivity-specific indicators listed in the GBF monitoring framework (Table 1), all of which have been developed for and tested in the terrestrial realm. To our knowledge, the applicability of these indicators to the marine realm has not yet been evaluated in the peer-reviewed literature. Further, some of these indicators require global land cover data, for which marine analogues (e.g. detailed habitat maps covering the global seafloor) do not exist. Thus, while most of these connectivity indicators could conceivably be applied to marine ecosystems they are limited by data availability, and their relevance remains to be tested. Overall, the indicators listed in the GBF could be used for individual species or certain ecosystems at local and regional scales. On global scales, the indicators could be used for coral reef ecosystems, as well as for migratory species with global ranges, such as seabirds or turtles.

Table 1: Approaches for measuring connectivity in the sea, including relevant indicators proposed for monitoring progress towards the Goals and Targets of the Kunming-Montreal Global Biodiversity Framework (GBF).
Adapted from Metaxas et al. (2024)[4].

What are we measuring?	What is the underlying process?	What is the tool/metric/measure?
Approaches using indicators in the GBF monitoring framework		
Protection of areas that are connected	Migration/Dispersal	Protected Areas Connectivity (ProtConn)[7]; % of the study region covered by connected protected "lands"/areas
Protection of areas connected through intact pathways	Migration	ConnIntact[8]; % of study region covered by connected protected "lands"/areas that are unimpacted by humans
Degree of isolation of individual PAs	"Migration (mammal movement)"	Protected Area Isolation (PAI)[9]; Isolation value of each PA based on effective resistance to movement
Number of PAs within a connected cluster relative to total number of PAs	Dispersal	Protected Network metrick (Pronet)[10]; Sum of the squared areas of PAs within each cluster, normalized by the square of the sum of areas for all PAs.
Proportion of actual connectedness of PAs	Migration	Protected Area Connectivity index (PARC)[9]; Weighted sum of connectedness of each grid cell/planning unit to all surrounding grid cells/planning units
Relative amount of connected compositionally similar natural habitat of a given spatial configuration	Migration	Bioclimatic Ecosystem Resilience Index (BERI)[11]; Global modelling of spatial turnover in species composition to assess changes in connectedness with shifts due to climate change
Longitudinal connectivity (dendritic system)	Migration (fish)	Dendritic Connectivity Index (DCI)[12]; Weighted average of coincidence probabilities across an entire system
Examples of existing approaches in the marine realm not included in the GBF		
Protection of physical features or areas that provide connectivity	"Various (non-specific)"	% of areas identified as providing connectivity and that are protected
Connectivity between habitats	Dispersal	Maximum distance for dispersal
Viability of habitats with few, weak or no connections	"Retention, Self-recruitment"	Size of protected area relative to dispersal distance
Importance in the network of habitats/ populations/MPAs/OECMs	"Various (non-specific)"	Betweenness centrality, Page Rank
Population structure	Gene flow	Genetic divergence, genetic structure, gene flow
Protection of migratory populations	Migration	Number of sets of linked Important Areas (spawning, feeding, mating, nesting), which are protected
Migratory connectivity	Migration	Betweenness, centrality, size of network, % based thresholds; strength of connectivity

To address potential shortcomings from the terrestrial basis of the existing indicators included in the GBF monitoring framework, we should prioritise the inclusion of functional connectivity indicators. Functional connectivity indicators such as network metrics are more applicable to the 90% of the planet that lies beyond coastlines, and are better suited to address the movement and migration of individuals, genes and species. Network-related analytical approaches range in complexity from simple rules of thumb (e.g., the size of a protected area relative to the distance to the next protected area) to graph theory metrics (e.g., centrality measures like betweenness).

Effectively incorporating connectivity into decision-making processes is challenging due to the complexities involved in developing appropriate targets for conservation objectives. The suggested functional connectivity indicators in Table 1 can help establish specific, measurable, achievable, relevant, and time-bound (SMART) targets. Marine and migratory connectivity metrics exist, and their inclusion in the GBF will help ensure that the global ocean is not an ocean apart from the Global Biodiversity Framework.

About this brief

This text was adapted from Bentley et al. (under review)[3] and Metaxas et al. (2024)[4]. We thank the co-authors for these excellent resources and encourage anyone interested in the topics of marine or migratory connectivity to read the full papers, which are listed below.

References and further reading

[1] Harrison AL, Costa DP, Winship AJ et al. (2018) The political biogeography of migratory marine predators. *Nature Ecology & Evolution*, doi: 10.1038/s41559-018-0646-8

[2] Dunn DC, Harrison AL, Curtice C et al. (2019) The importance of migratory connectivity for global ocean policy. *Proceedings of the Royal Society B*, doi: 10.1098/rspb.2019.1472

[3] Bentley L, Nisthar D, Fujioka E et al. Marine megavertebrate migrations connect the global oceans, 12 June 2024, PREPRINT (Version 1) available at Research Square: doi: 10.21203/rs.3.rs-4457815/v1. Under review at *Nature Communications*.

[4] Metaxas A, Harrison AL & Dunn D (2024) From oceans apart to the global ocean: Including marine connectivity in global conservation targets. *npj Ocean Sustainability*, doi: 10.1038/s44183-024-00079-1

[5] Balbar AC & Metaxas A (2019) The current application of ecological connectivity in the design of marine protected areas. *Global ecology and conservation*, doi: 10.1016/j.gecco.2019.e00569

[6] Beger M, Metaxas A, Balbar AC et al. (2022) Demystifying ecological connectivity for actionable spatial conservation planning. *Trends in Ecology & Evolution*, doi: 10.1016/j.tree.2022.09.002

[7] Saura S, Bastin L, Battistella L et al. (2017) Protected areas in the world's ecoregions: How well connected are they? *Ecol. Indic.* 76, doi: 10.1016/j.ecolind.2016.12.047.

[8] Ward M, Saura S, Williams B et al. (2020) Just ten percent of the global terrestrial protected area network is structurally connected via intact land. *Nature Communications* 11, doi: 10.1038/s41467-020-18457-x

[9] Brennan A, Naidoo R, Greenstreet L et al. (2022) Functional connectivity of the world's protected areas. *Science* 376; doi: 10.1126/science.abl8974

[10] Theobald DM, Keeley ATH, Laur A & Tabor G (2022) A simple and practical measure of the connectivity of protected area networks: The ProNet metric. *Conservation Science and Practice* 4, doi: 10.1111/csp2.12823

[11] Ferrier S, Harwood TD, Ware C & Hoskins AJ (2020) A globally applicable indicator of the capacity of terrestrial ecosystems to retain biological diversity under climate change: The bioclimatic ecosystem resilience index. *Ecological Indicators* 117, doi: 10.1016/j.ecolind.2020.106554

[12] Cote D, Kehler DG, Bourne C & Wiersma YF (2009) A new measure of longitudinal connectivity for stream networks. *Landscape Ecology* 24, doi: 10.1007/s10980-008-9283-y

FOCUS

How migratory species connect the global ocean

Migratory species movements can be both enormous in scale and transboundary in nature. Leatherback turtles, for example, have been known to travel from Oregon to Indonesia – more than 20,000 km. As animals move across vast areas, they encounter a diverse suite of threats that makes understanding those movements critical to their management[1]. Over the last 30 years, advances in animal tracking technology have provided lighter and longer-lasting tags, allowing us to follow more species on their journeys, further across the planet. However, information about migratory movements sits in thousands of disparate sources, making understanding the true scale of connectivity for any species (much less all species) very difficult to assess[2]. A new tool and publication[3] are shining a light on the minimum global connectivity of marine migratory species.

The freely-accessible, cross-taxa, interactive connectivity models available online through the Migratory Connectivity in the Ocean system (MiCO; mico.eco/system) provide a critical resource describing global-scale connectivity for migratory fish, seabirds, marine mammals and sea turtles. Understanding how these species journey between EEZs allows parties to identify the key collaborative partners required to implement successful conservation across their migratory cycles. Furthermore, migratory connectivity – and connectivity in general – are also essential considerations in the design and development of marine protected areas [5,6].

While the extensive migratory connectivity synthesised in the system is astonishing, it also points out major gaps in our understanding of their movements, both geographic and taxonomic. As the system does not show all oceanic migratory connectivity, but the minimum connectivity that has been measured, the gaps within the system can be informative. For example, tropical seabirds are relatively understudied in comparison to those from the Southern Ocean, and most of our knowledge on sea turtle movement comes from females, not males. Many of these data gaps are also linked to differences in investment in research and conservation between the Global North and the Global South. To fulfill commitments under the GBF, and truly understand progress toward targets, significant and equitable further research and synthesis is necessary.

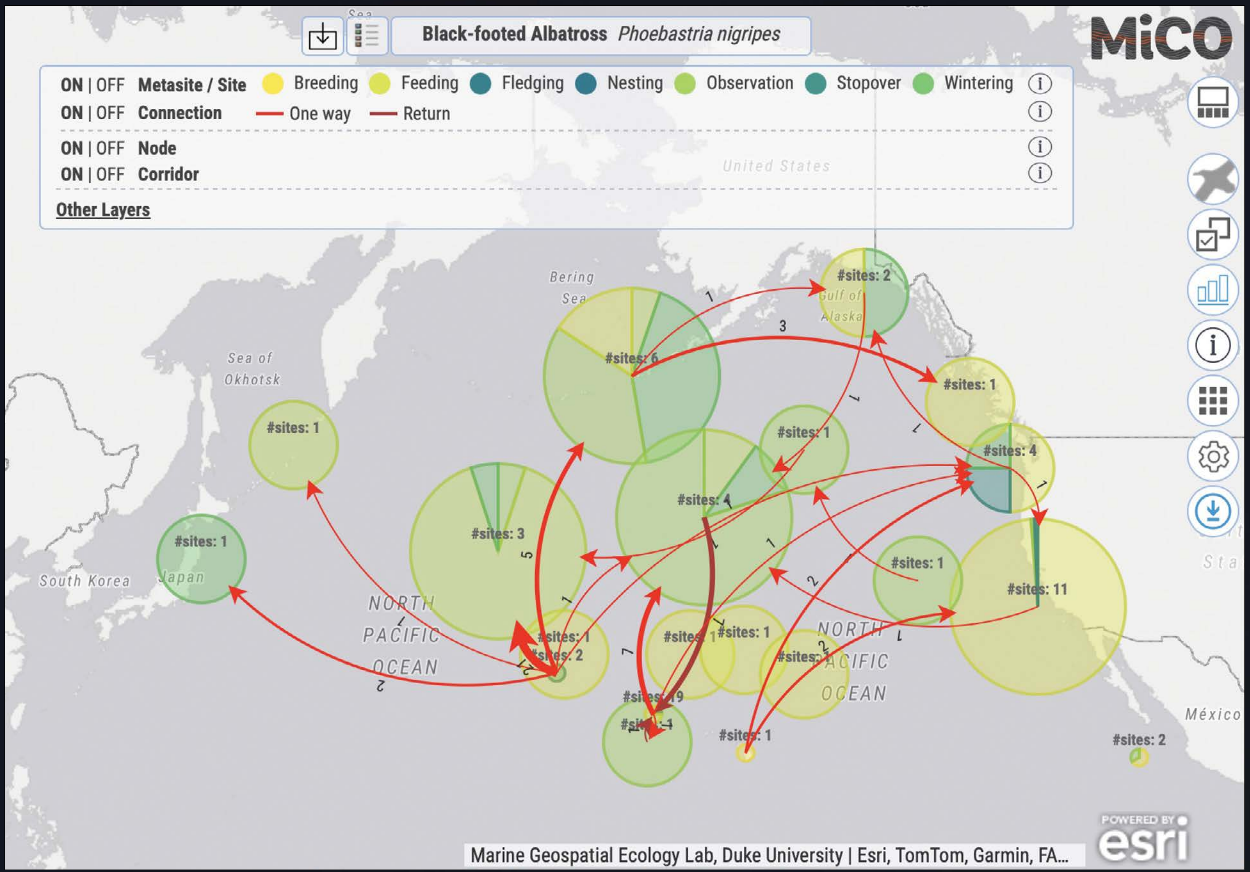


Figure 1: Web interface showing example synthesised global connectivity models for the black-footed albatross. The number of combined sites (#sites) is noted for each circular metasite. Colours indicate known behaviour associated with each metasite (e.g. breeding, feeding). Red arrows indicate known links between locations, with the number adjacent to the arrow indicating the minimum number of known individuals connecting the two metasites. View the dynamic versions of these and over 100 other network models at mico.eco/system/mapper

Figure 2: Minimum region-to-region individual connections summarised from the MiCO system for seabirds. Shades indicate the key regional groups: Africa (red), the Americas (green), Asia (orange), Europe (blue), Oceania/Antarctica (purple), and areas beyond national jurisdiction (grey). Note that because start-end locations of movement were summarised rather than complete tracks, these diagrams do not include links to regions through which animals transited, and as such represent minimum connectivity. Figure from Bentley et al. (under review)[3].

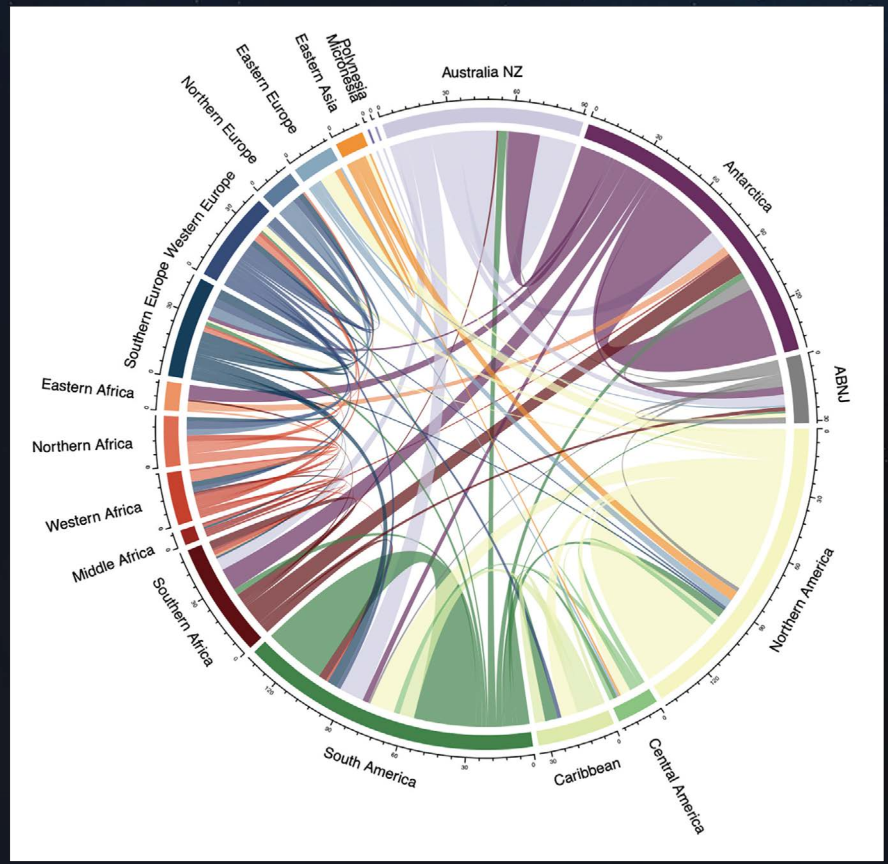
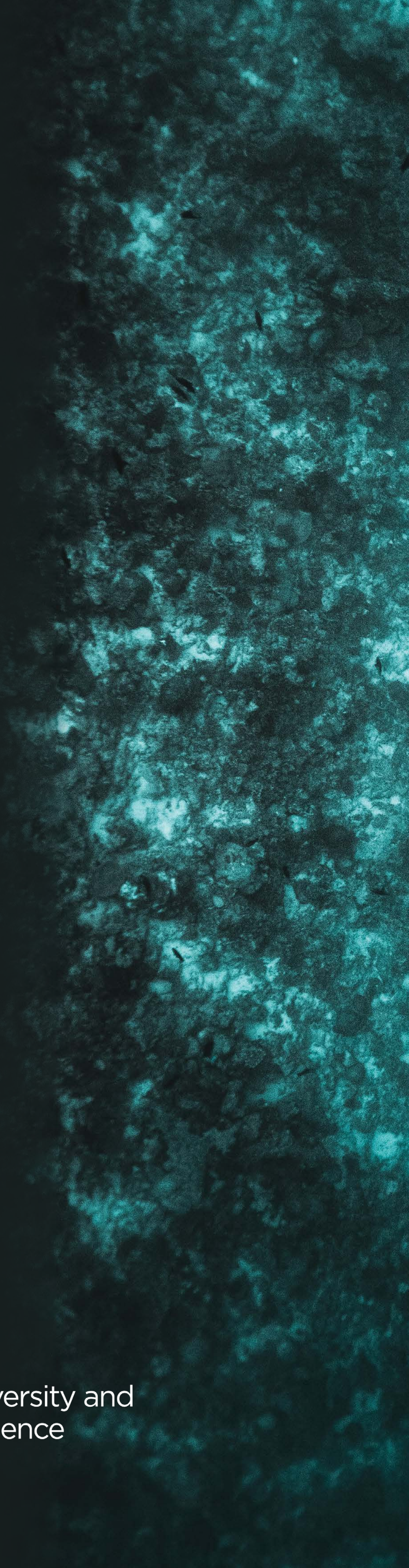


Photo credits:
Cover: Ishan Hassan / Ocean Image Bank
Coral spawning (p1): shutterstock
Sea turtle (p2): rayyu/unsplash
Manta ray (p2): AnettSzaszi/Ocean Image Bank
Red-billed tropicbird (p5): Daniel Dunn
Sardines and marlin (p4): shutterstock
Humpback whale (p6): Gabriel Dizzi/unsplash



This policy brief is brought to you by:

GOBI
Global Ocean Biodiversity Initiative

DOSI
DEEP-OCEAN STEWARDSHIP INITIATIVE

DALHOUSIE UNIVERSITY

THE UNIVERSITY OF QUEENSLAND AUSTRALIA

Centre for Biodiversity and Conservation Science