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Bioregions of the South West Pacific and Indian Ocean

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1 Introduction

Global oceans are experiencing an increasing variety of uses and are experiencing increasing impacts from these activities. There is global agreement that the best approach to managing these uses is through an Ecosystem Approach. Best practice is based on 2 principles, 1) it is done with an ecosystem approach and 2) it is place based. To implement this, management requires several key pieces of information; where do different ecosystems occur, what species do they contain and what are their dynamics. Understanding ecosystem dynamics has been a key focus of fisheries science, while understanding the spatial bounds and identities of species has been a key focus of conservation science. Putting these two fields together will allow an ecosystem-placed based approach.

Biogeographic regions are a useful descriptor of biological units, that integrates ecological and evolutionary processes. Bioregions provide spatially discrete units that can be used as part of an Ecosystem Approach to management. Ideally, these describe ecosystems within an area and describe the contained within each region. Historically, bioregions have featured predominantly in conservation planning (Last et al. 2010), but more recent applications into fisheries have demonstrated their broader applicability (Koen-Alonso et al. 2019). Alternative approaches to management, focusing on ecosystem dynamics, have been developed primarily through fisheries research. These models describe the way that functional groups and species interact with each other and allow predictions of how a system will change under different pressure scenarios.

There have been significant efforts previously to describe bioregions in the world's oceans. There have been previous descriptions of the epipelagic (Longhurst 2010, GOODS (UNESCO 2009), Sayre et al. 2017ef), mesopelagic (Sutton et al 2018) and benthic (Spalding et al. 2007, Oboura 2012 , GOODS (UNESCO 2009)). However, each of these has been an independent effort and did not always include regional expertise. Consequently, each effort provides a partial picture of the distribution of biodiversity across the full oceanic realm. We have merged these existing regionalisations and updated them with detailed regional knowledge to produce a single set of bioregional provides that describes the benthic and pelagic ecosystems of the Indian and Pacific oceans.

The development of new bioregions draws on experience in CSIRO, Global Ocean Biodiversity Initiative (GOBI) partners, and other collaborators, using approaches currently being trialled in Australia and around the Antarctic margins, and has collaborated with regional and national stakeholders to ensure a consistent approach. This combines approaches CSIRO developed in Australia (Last et al. 2010), used in the Bay of Bengal (BOBLME 2015) with similar approaches that have been used throughout the Indian and Pacific Oceans to derive a single combined bioregionalisation.

The new bioregionalisations for the south west Pacific and Indian Oceans incorporate understanding of shallow, deep and pelagic species, ecosystems, physical environments and their likely boundaries based on current information. The expert-based bioregionalisations are be supported by development of statistical analysis of datasets of selected species groups to identify bioregions specific for each taxon, with data from the Biologically or Ecologically Significant Marine

Areas (EBSA) process and additional regional biogeography based on new invertebrate and fish collections from CSIRO, University of Tasmania, Museum Victoria and regional partners.

2 Process to Develop Bioregionalisations

2.1 Place based descriptions of bioregions

The regionalisations of the South West Pacific and Indian Oceans were based on a hierarchical approach that considered the relationships between physical processes, geological and oceanic features, evolutionary processes and ecological communities. The relationships between these different structuring processes are considered at a number of different spatial scales. At the largest scale we have separated the two ocean basins. Within the ocean basins we have identified large scale marine regions that define the major oceanographic or geological features and boundaries and define the evolutionary bounds of multiple taxa. Finally, we define provinces within the marine regions that describe areas where the same group of species is expected to occur. The province level will contain unique ecological communities and endemic species that have evolved together over time and may have physical and biological interdependencies.

Table 1 Hierarchical Scales of Biogeographic Classification (Derived from Last et al 2010)

Classification Level	Scale, Key Driver	Characteristics
Ocean Basins	Basin circulation, climate change, water masses, tectonics, terrestrial inputs, continental drift and basin evolution.	Unique ocean-scale composition of environments including tectonics, exchanges with other oceans, paleo-evolution of flora and fauna composition.
Large Marine Regions	Portions of the ocean basin that have evolved through formation or breakdown of barriers and environments. Tectonics (volcanic activity, plate collisions) and ocean circulation are important rivers at this scale.	Unique subset of basin environment caused by changes in drivers and/or physical structure of sub-basin. Environmental and Evolutionary differentiation of faunal compositions and formation or isolation of unique fauna. Contains a collection of provinces.
Provinces	Units within basins with distinct fauna evolved under distinct paleohistoric pathways and processes: barriers (submergence, emergence), circulation, deep water formation and upwelling, mode water formation, water mass renewal and terrigenous inputs	Core provinces contain unique biota within an environment that is differentiated at the sub-basin scale. Speciation aided or hindered by physical processes and moderated by biological adaptive evolutionary processes resulting in a suite of endemics species that adhere to the province unit. Transitional provinces of mixed environments may contain a mix of species from adjoining core provinces.
Geomorphic Types	Distinct geophysical Units (e.g. seamounts, Undersea volcanoes, mudflows, ridges, trenches and channels) that	Faunal unit adapted to environment and habitat niches provided by the geomorphic unit and its contained environment.

	act as surrogates for distinct fauna associated with the unit. Unit provides differential exposure to environment, exchanges and energy flows.	
Habitats/Facies	Hard, soft or mixed substrates formed by various degradation and erosive processes with by-products accumulating within certain areas.	The composition and texture of facies units provide substrates that serve a variety of purposes for flora and fauna.

This organisation of the classification of biodiversity recognises the spatial hierarchy of biodiversity at a range of scales as detailed in Last et al. (2010).

The hierarchical approach recognises the interplay between processes acting at large scales down to processes acting at metre scales and allows the description of biodiversity at each of these scales. However, for this project we are limited to describing biodiversity at the ocean basin, large marine region and province/bathome scale. To move down to the characterisation of geomorphic types and habitats would require additional information and data at smaller scales. Information at this scale is often held by national governments

To augment this information we relied on biological and ecological information from experts to guide and verify the descriptions of the marine regions and provinces and describe the biophysical interdependencies. For each province, we captured these dependencies through descriptions and concept illustrations that show the defining aspects of the physical drivers, features and processes, and the associated biological communities. These illustrations are useful in understanding the complex biophysical drivers and dependencies, and they also communicate the unique aspects of each province. These illustrations can be used as context to extend the regionalisation to smaller scales in the future.

The participatory approach for the regionalisation involved two workshops and subsequent refinements between CSIRO scientists and local experts. To prepare for the first workshop, CSIRO scientists collated information from literature sources and local experts to map the physical environment, habitats and species distributions. After the approach was explained to workshop participants, the mapped products, Traditional and Local knowledge were used to describe the regionalisation and to describe the features, processes and interrelationships within each province and between provinces. These relationships were then schematically illustrated by working groups set up for each province. Post-workshop activities refined these draft regionalisations by following up on missing information and ensuring consistency in the descriptions and illustrations. The second workshop reviewed the regionalisations and completed the systems descriptions of each province and linkages between provinces. This latter aspect also facilitated work on trans-boundary issues.

2.2 Conceptual Models of Ecosystems within Provinces

To better manage and maintain the components of ecosystems contained within bioregions, we need to understand how important components function. One approach to elicit these interdependencies and interactions of key ecosystem characteristics to describe a system using conceptual models. Conceptual models represent a working hypothesis about how an ecosystem works. They should: a) identify the important components and processes in the system; b) document assumptions about how these components and processes are related; c) identify the linkages between these components/processes and anthropogenic pressures; and d) identify knowledge gaps or other sources of uncertainty.

Conceptual models come in many different forms including simple narrative descriptions, schematic diagrams, box-and-arrow flowcharts, or even cartoons that pictorially illustrate physical and biological processes and the effects of anthropogenic pressures. Even though there are many forms of conceptual models, they all hold common elements and can be constructed using a common set of steps.

Steps or tasks in constructing conceptual models:

1. Identify bounds of the system of interest
2. Identify key model components, subsystems, and interactions
3. Identify natural and anthropogenic stressors (pressures)
4. Describe relationships of stressors, ecological factors, and responses

Conceptual models need to portray the ecological system at a level of resolution that is useful to the purposes of the risk assessment, striking a balance between simplicity and complexity. They should not seek to represent the entire system with myriad components and processes; rather the goal should be to encompass the relevant subsystem, which includes the components of the system that are the focus of the risk assessment, the associated processes and variables that act to maintain and regulate them, and the natural and anthropogenic pressures or concern.

The conceptual model is represented by functional groups (nodes in the diagrams) and relationships between the nodes, indicated by lines terminating in either a solid circle or an arrow. A line terminating in a circle indicates that there is a negative relationship between the functional groups (e.g. Predatory Fish (PF) consume and impact Deposit Feeders (DF); -1). A line terminating in an arrow indicates a positive relationship between the two functional groups (e.g. Sessile Filter Feeders (SFF) consume Phytoplankton (PP); +1). A predatory relationship is indicated by a solid circle and an arrow going in opposite directions. A competitive relationship is indicated by two solid circles. A symbiotic relationship is indicated by two arrows. The response of the ecosystem to pressures (e.g. fishing gears, temperature and shipping) can be analytically calculated from this system using the numerical values of the links between the ecosystem components. The response from a qualitative model can be viewed only as a directional change in the abundance (count, occurrence or presence) of each functional group. A negative value indicates a decline in that functional group, a positive value indicates a increase in that group, while values between -0.25 and 0.25 are deemed ambiguous and the direction of response is not known (but thought to be small).

Experts in the workshops constructed conceptual models of the dominate ecosystem in each province and described the key ecosystem components and the links between these components. The experts then identified the pressures acting the system and where and how those pressures would interact with the system that had been described in the conceptual model.

2.3 Data on the Structure of the Pacific Ocean

Understanding the ecology and biology of the Indian and South West Pacific Ocean requires extensive collections of data to support the analysis and description of the different bioregions with the basin. The South West Pacific Ocean extends from the Eastern Coast of Australia to approximately 100°W Longitude, to the north to 10°N Latitude and extends nominally south the boundary of the CCAMLAR region. The Indian ocean extends from the Eastern Coast of Africa to the Western Coast of Australia, to the north to the Bay of Bengal and the Arabian Sea and extends nominally south the boundary of the CCAMLAR region.

In order to develop an understanding of the Biology, Ecology and Physical structure of the Indian and South West Ocean a significant number of data sets were collected. These are shown in Table 2.

Table 2: List of data sets used as part of the bioregionalisation exercise

Biological data set	Biological/Ecological data	Previous Bioregionalisations
Bathymetry (GEBCO 2014)	Squat Lobster Statistical regionalisation – 4 Specie Groups (CSRIO 2018)	Regional Provincial Provinces (National Marine Bioregionalisation of Australia 2005; Brewer et al. 2015; Douglas et al. 2015; Sink et al. 2010)
Geomorphology (Harris et al. 2014)	Ophiuroid Statistical regionalisation – 6Specie Groups (CSRIO 2018)	Regional Pelagic Regionalisation (National Marine Bioregionalisation of Australia 2005; Lyne and Hayes 2005; Raymond 2017; Brewer et al. 2017).
Simplified Geomorphology (Harris et al. 2014)	Distribution of Coral Reefs and Species Richness (Bugura and Obura, 2010, CORDIO; UNEP WCMP, World fish centre, WRI, TNC (2010)	Surface Ecological Units V1 Ocean ESRI,(Sayre et al 2017)
Chlorophyll a Concentration June and December Means (NOAA)	Distribution of Coral Reefs UNEP WCMP World fish centre, WRI, TNC (2010)	Ecological Marine Units DepthV1 Pacific Ocean 1000m Esri
Sea Surface Temperature June and December Means (NOAA)	Distribution of Seagrass (UNEP WCMC 2005; Short 2017)	Bottom Exologica; Units V1 Pacific Ocean Esri
Nitrate Decadal Averages – Sea Surface, 200m, 500, 1000m, Seafloor; (WOA 2018)	Distribution of Mangroves (Spalding et al. 2010)	Mesopelagic Ecoregions V1 2017. (Sutton et al. 2017)
Oxygen Decadal Averages – Sea Surface, 200m, 500, 1000m, Seafloor; (WOA 2018)		Marine Ecosystems of the World (MEOW) Spalding et al. 2007
Temperature Decadal Averages – Sea Surface, 200m, 500, 1000m, Seafloor; (WOA 2018)		Large Marine Ecosystems (LME) NOAA
Density Decadal Averages – Sea Surface, 200m, 500, 1000m, Seafloor; (WOA 2018)		

Silicate Decadal Averages – Sea Surface, 200m, 500, 1000m, Seafloor; (WOA 2018) Phosphate Decadal Averages – Sea Surface, 200m, 500, 1000m, Seafloor; (WOA 2018)	Longhurst Biogeographical Provinces (Longhurst et al. 1995) Global Open Oceans and Deep Seabed (GOODS) Pelagic Provinces. WWF Global Open Oceans and Deep Seabed (GOODS) Bathyal Provinces.

3 Bioregions of the Indian and South West Pacific Ocean.

The workshops described a total of 26 large marine regions and 146 provinces in the South West Pacific and Indian Ocean. The boundaries for each large marine region and each province are detailed in the Annexes for each Ocean basin and include a text description of the key ecosystems of each province, a qualitative model that describes the ecosystem components and pressures on the system and a scenario analysis of the likely impacts of the pressures on the ecosystem where they occur. As identified in O'Hara (2011), we see biodiversity distributed in latitudinal bands in both the pelagic and benthic realms – patterns that are consistent across depths and ocean basins.

However, the longitudinal patterns and the details of the pelagic and benthic systems are substantially different.

Table 3: Count of the number of Large Marine Regions and provinces in the Indian and South West Pacific Oceans

South West Pacific	Large Marine Regions	Provinces
Pelagic	9	21
Benthic	4	35

Indian	Large Marine Regions	Provinces
Pelagic	8	14
Benthic	5	76

Pelagic large marine regions and provinces in the Indian and South West Pacific are structured in similar ways. The pelagic ecosystems are characterised by large pelagic marine predators such as tuna, that are the focus of significant fisheries. The bioregions are ordering in latitudinal bands, except around continental masses where topographic features break the oceanic gyre patterns. The qualitative models are also similar between the ocean basins, demonstrating that the pelagic systems are functions in similar ways between the oceans and share many of the same higher species.

However, there are more benthic provinces than pelagic provinces, despite fewer large marine regions. This is in part due to the large number of depth zones that the benthic provinces cover. The benthic provinces extend from the shelf (0-200 m) through bathyal depths (200 – 3500m) and into the abyssal depths. Depth is one of the major structuring features of benthic systems which partition geographic areas into different provinces – shelf regions are fundamentally different to the bathyal and abyss. The centre of the two ocean basins the Coral Triangle, which is a global region of evolutionary diversification (Obura 2012, Carpenter et al. 2011) and serves as a source for the evolution of many species.

Distance from the Coral Triangle is a key predictor of species diversity in shelf areas in the Pacific and Indian oceans (Carpenter et al. 2011, Obura 2012, Sheppard 1987, Veron 2000). Areas close to the Coral Triangle have the highest diversity of both hard corals and fish, with species richness decreasing as distance increases. Both basins also cover extensive latitudinal bands which also increases species diversity. Deep sea species may also show similar patterns. Many bathyal and abyssal species are evolutionary associated with continental boundaries which may function as the basis for evolutionary lineages in the deep sea (O'Hara et al 2019). This would suggest that the highest diversity is associated with the areas close to boundaries, with diversity in the deep sea decreasing as the distance from a continental shelf increase. The continental shelf/slopes generate the smallest scale variation in biogeographic patterns and from an evolutionary diversification perspective, the shelf is new and rapidly radiated.

The qualitative models of ecosystems also share similarities. Although the species are different, the models for coral reef, mangrove and soft sediment shelf ecosystem are similar in both the Indian and South West Pacific Oceans. The same pattern can be seen in the slope and abyssal ecosystems, different species but similar functional groups and links. However, key differences emerge when considering the different pressures that are acting on these systems. Typically, shelf systems are under more pressure than slope or abyssal systems, but there are some shelf systems, particularly in remote atoll systems, that have a limited number of pressures. The most common pressure identified was climate change, either through warming or acidification.

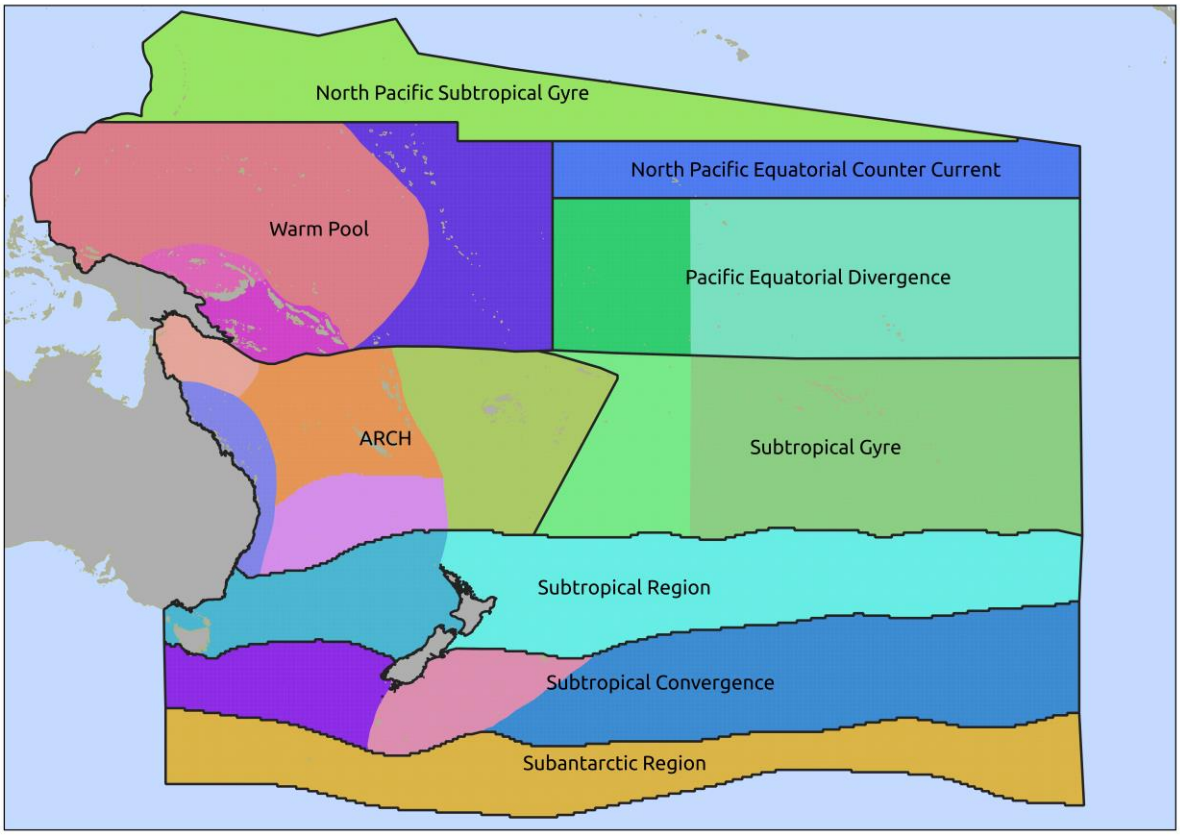

Figure 1 The pelagic Large Marine Regions (outlined and named) and provinces (coloured) in the South West Pacific Ocean.

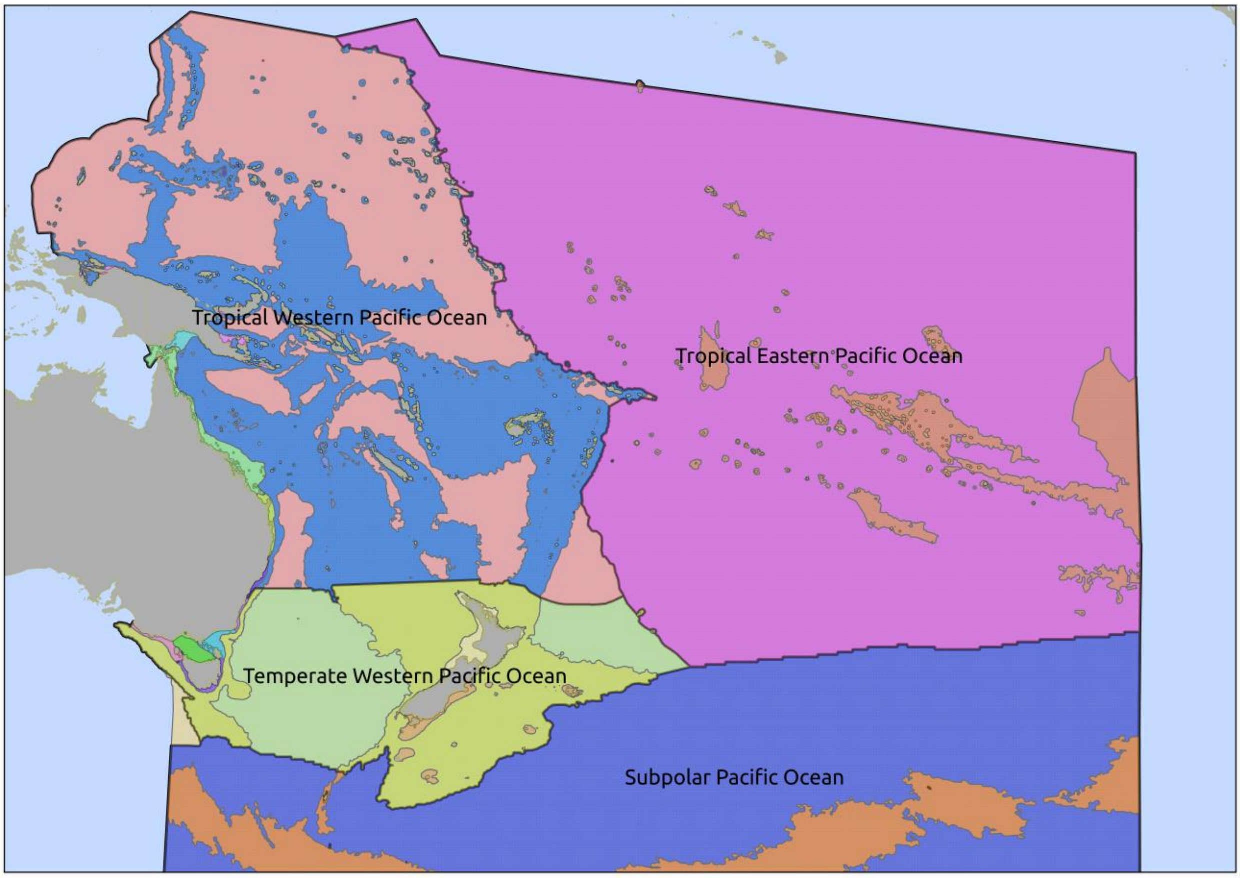

Figure 2: The benthic Large Marine Regions (outlined and named) and provinces (coloured) in the South West Pacific Ocean.

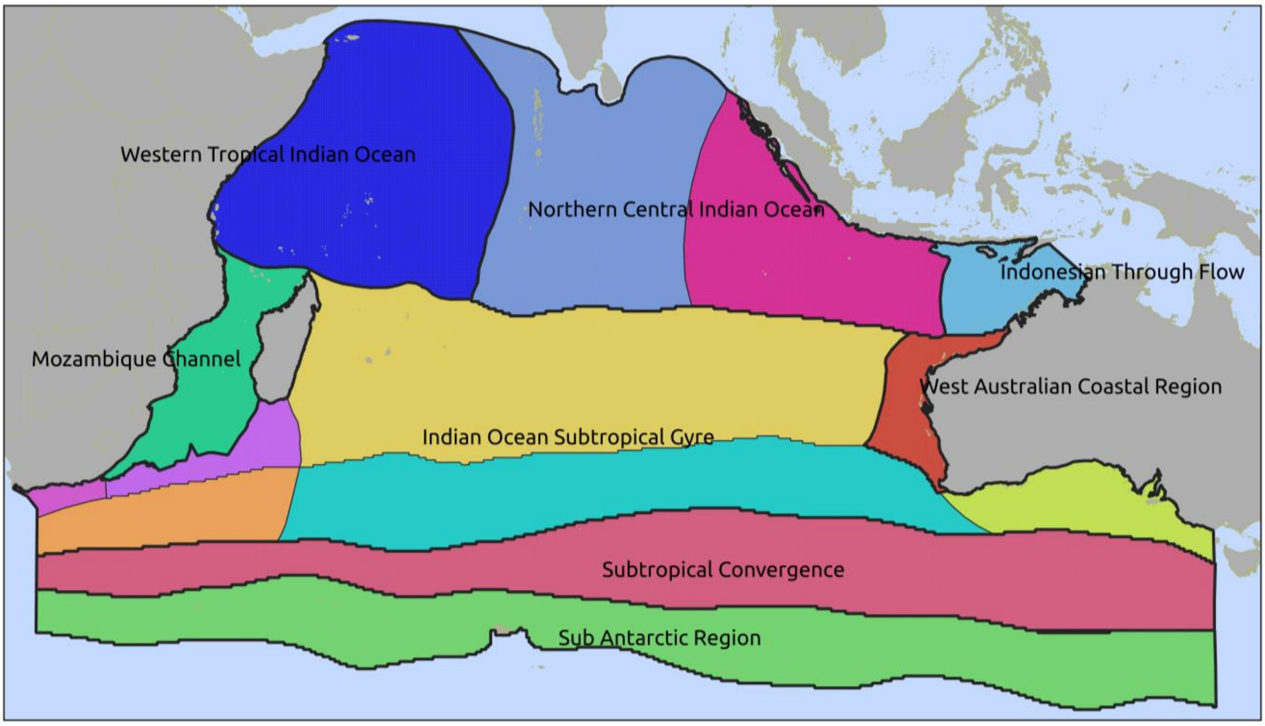

Figure 3 : The pelagic Large Marine Regions (outlined and named) and provinces (coloured) in the Indian Ocean.

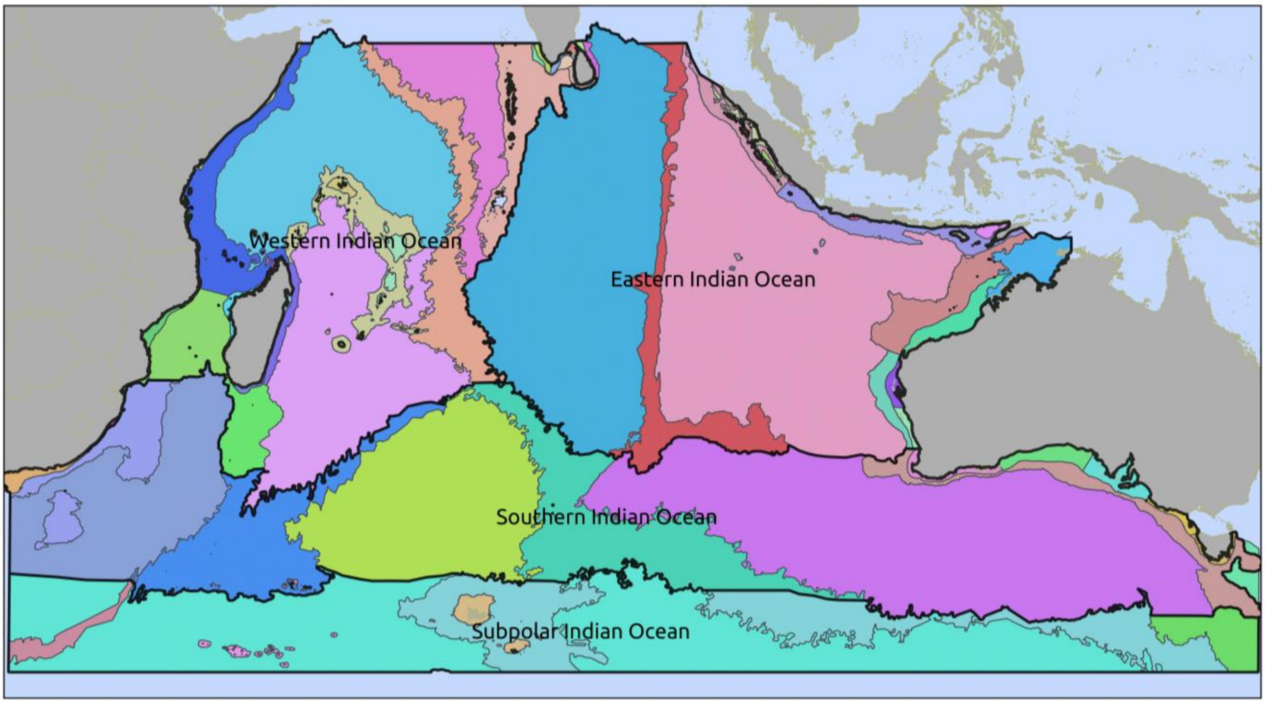

Figure 4: The benthic Large Marine Regions (outlined and named) and provinces (coloured) in the Indian Ocean.

4 Management and Conservation

Effective ecosystem-based management relies on understanding ecosystem function and location. Types of management similar to that outlined by Koen-Alonso et al. (2019) allow for both the conservation and sustainable use of the marine environment. Understanding where impacts are likely to occur and on which parts of the ecosystem will allow more focused management that can mitigate the most significant impacts and identify the areas that need to be protected.

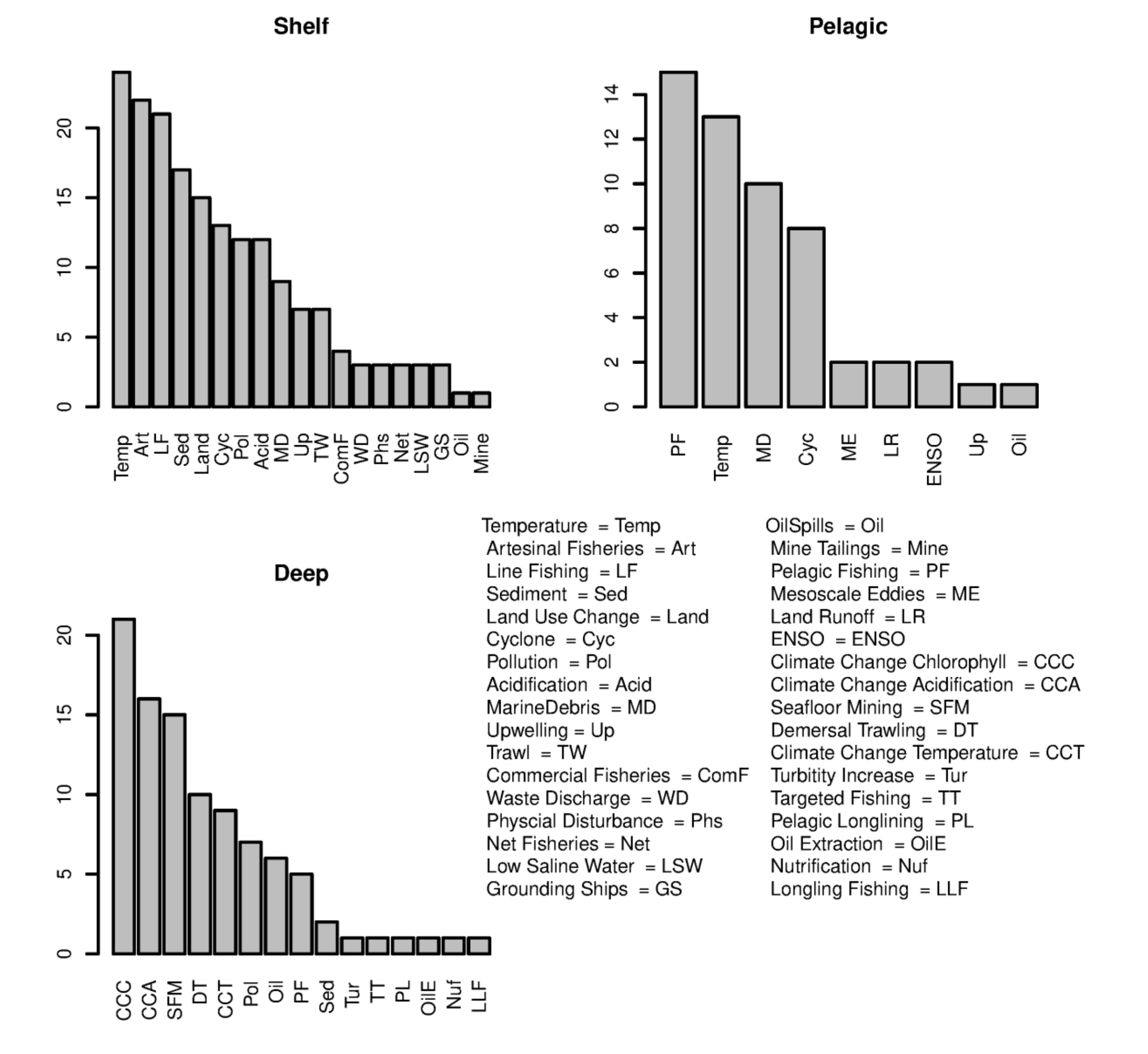

Figure 5: Count of pressures identified on shelf ecosystems (0-200m), Deep ecosystems (200-6000m) and Pelagic ecosystems.

This work provides a holistic overview of the Indian and South West Pacific Oceans, the ecosystems that occur there and the pressures that are on those ecosystems. The most common pressures identified were associated with Climate Change, (ie increases in temperature and acidification and changes to chlorophyll supply). Fisheries were also an important pressure across all ecosystems for a range of different gear types (eg Trawl, Long Line, Net). The models also identified sedimentation and land use change as major concerns in coastal systems and identified potential future pressures such as seabed mining. The qualitative models could allow different jurisdictions to take a precautionary approach to the diversity of pressures in each province and exchange ideas on management for provinces that have identified similar ecosystems.

The diversity of pressure that are occurring across the Indian and South West Pacific Oceans highlights the need for a proactive move toward integrated management of the oceans that combines conservation measures (such as MPA) with best practice sustainable use management (such as harvest management strategies) to manage all the impacts that have and continue to occur.

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