

Coastal biodiversity in the Indian Ocean: The known, the unknown and the unknowable

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In this review, the biodiversity of the coastal marine regions of the Indian Ocean is contrast with that of the Pacific and Atlantic oceans. We discuss the important types of coastal habitats (coral reefs, mangrove forests and seagrass meadows) in the Indian Ocean and their use as proxies for biodiversity. An overview of what is known of coastal marine biodiversity in different parts of the Indian Ocean is assessed by using comparable information on some of the better-known taxonomic groups including corals, mangroves, seagrasses, fishes, marine mammals, turtles, crustaceans and molluscs. We also discuss important gaps in our knowledge and aspects of the biodiversity that will never be determined either because of changes that have already occurred or because we cannot increase our knowledge at a rate relative to anthropogenically induced change. A framework is proposed for the Indian Ocean based around international cooperation to increase our understanding of biodiversity based on ecosystem bioregionalisation and linkage of this to mechanisms ensuring protection of important and representative areas of coastal marine biodiversity.

[Key words: Indian Ocean, biodiversity, coastal, marine, endemism, bioregion]

1) Introduction

The Indian Ocean is the third largest of the world's great oceans. The boundaries of the Indian Ocean are roughly defined from the African coast at 20°E to the Australian and Indonesian coasts in the west, and from being landlocked in the north by the Indian subcontinent to 60°S south where it meets the Southern Ocean. It is defined to include the Red Sea, Andaman Sea, Arabian Sea, Flores Sea, Gulf of Aden, Gulf of Oman, Java Sea, Persian Gulf, Savu Sea and Strait of Malacca, with 38 countries making up the coastal states of the Indian Ocean region. The principal bathymetric features of this ocean are the Southwest Indian Ridge and Mid-Indian Ridge in the west and the Southeast Indian Ocean Ridge and Ninetyeast Ridge in the east. The Indian Ocean region's climate is dominated by the northeast monsoon (December to April) and southwest monsoon (June to October) and the currents that these produce. Tropical cyclones occur during May/June and October/November in the north and January/February in the south of Indian Ocean.

The Indian Ocean nations have a combined coastline length¹⁻⁵ of 66,526 km, which is only about half that of the Pacific and Atlantic oceans (Table 1).

The countries with the longest coastlines and marine exclusive economic zones (EEZs) are Australia, Indonesia and India^{1,3,5}. Approximately 15.9% of the Indian Ocean area is continental shelf, with some coastal countries having continental shelf areas large in comparison to their coastline^{5,6}.

Many of the countries of the Indian Ocean region are among the world's most populous and are also the poorest. Table 1 shows the combined population for Indian Ocean rim countries of 2.1 billion with a combined country GDP of US \$ 2662 billion, compared to the Pacific with a population of 2.7 billion and combined GDP of US \$ 18692 billion. Twenty-eight of the 38 Indian Ocean rim countries have more than half their populations living within 100 km of the coast⁵. Worldwide approximately 50% of each countries population live in the coastal zone; projections indicate this could increase to 75% by 2020⁷. With the majority of people living in the coastal areas of the world, those with the greatest population and fewest resources, such as many Indian Ocean rim countries, will have the most impact on the marine environment.

In this review we describe the coastal marine biodiversity of the Indian Ocean region. Our approach

Table 1—Comparison of major oceans based on selected physical parameters

	Atlantic Ocean	Indian Ocean	Pacific Ocean
Area (million km ²) ¹	76.8	68.6	155.6
Coastline (km) ¹	111 866	66 526	135 663
Continental Shelf Area (million km ²) ²	22.9	10.9	26.1
Population (millions) ^{1,3 *}	1702	2089	2701
GDP (billion US dollars) ^{1,3 *}	23671	2662	18692
Coral Reef Area (km ²) ^{3 *}	27040	161060	210990
Mangrove Area (km ²) ^{3 *}	43023	91170	92488
FAO Fish Catches (million tonnes)-LANDED ⁴	22.5	6.5	52
-DISCARDED ⁴	8	2.5	17

* figures considered to be overestimates (calculated by the sum of all countries bordering the ocean including those which may be divided over two oceans). For the Atlantic Ocean countries bordering the Mediterranean and North Seas were included but those on the Baltic and Black Seas coasts were not.

Source references: 1, 2, 3, 4

has been to use what is known about key species groups and habitat types to provide a picture of comparative biodiversity and demonstrate the status of knowledge rather than any accurate overall assessment of the biodiversity of either the region or any particular country. We have used regional assessments including web based tools rather than country based assessments to enable useful comparisons of regional biodiversity. We have not attempted to assess the extent of knowledge about all taxa either within the Indian Ocean or the comparative degree of knowledge between countries.

Additionally, we have sought to provide a picture of the level of threat to biodiversity as a result of pressure on coastal habitats in the Indian Ocean. We also provide some suggestions on moving forward to increase the level of knowledge of, and protection for, biodiversity in the coastal regions of the Indian Ocean. For the purpose of this assessment, the coastal zone is defined as all intertidal and subtidal areas on and above the continental shelf to a depth of 200 m. It is important to note that it covers only marine habitats and waters, and not estuarine areas.

2) Coastal Marine Biodiversity-The Known

The biodiversity of the Indian Ocean region, like most of the world's marine domain, is poorly known. As such, we have used a range of proxies known to harbour high biodiversity, these are coral reefs, mangrove forests and the number of seagrass species. While area of seagrass meadows was not available, seagrass species often vary in their physical habitat requirements, thus a high number of seagrass species

can be a good indicator of diverse and complex habitats dominated by seagrass.

For species diversity we examined the number of coral, mangrove, seagrass and fish species by country and compared the Indian Ocean with the Pacific and the Atlantic. Where available we have also used data on cephalopods, lobsters, shrimps, molluscs, marine mammals and turtles although much of this information was available to us only on a regional basis and not by individual countries.

2.1) Distribution of habitat types

About 80% of all marine species occur in the coastal zone⁸⁻¹⁰ and this figure is probably conservative¹¹. This concentration of diversity is associated with the complex habitats created by dominant benthic primary producers and the productive shallow waters fuelled by terrestrial inputs and upwelling. Soft bottom habitats with sparse vegetation are probably the most wide spread coastal marine type globally¹². Other habitat types of coastal ecosystems include coral reefs, mangrove mangals, seagrass meadows, algae and kelp forests, subtidal rocky reefs and intertidal rock platforms, as well as the pelagic. Of these coral reefs, mangroves, algal dominated rocky reefs and seagrass meadows have the most complex community assemblages and thus the highest biodiversity. Corals, mangroves and seagrasses are also among the taxa whose biodiversity is best known, making them ideal proxies for assessing biodiversity.

Coral reefs and mangroves systems occur¹² principally between 30°N and 30°S. Coral reefs are

amongst the world's most biodiverse habitats¹¹ and they occupy less than 1% of the world's continental shelf area¹². The area of coral reefs in the Indian Ocean is 161,000 km², intermediate to that of the Atlantic (27,000 km²) and Pacific (211,000 km²) oceans (Table 1). More than 90% of the global coral reef area is within the Indo-Pacific¹³, with Indonesia (51,000 km²) and Australia (49,000 km²) making up almost half the world's coral reefs (Table 2). Other Indian Ocean countries with extensive coral reef areas are the Maldives (8920 km²), Saudi Arabia (6660 km²) and India (5790 km²) (Table 2).

The Indian Ocean has 91,000 km² of mangroves, this is about twice that in the Atlantic (43,000 km²) and similar to the Pacific Ocean (92,000 km²) (Table 1). Table 3 shows that the Indian Ocean countries with the highest areas of mangrove forests are in the central and eastern area, namely Indonesia (42500 km²), Australia (11500 km²), India (6700 km²) and Malaysia (6424 km²). The greatest area of mangroves in the western Indian Ocean is in Madagascar with 3403 km² (Table 3). While Indian Ocean countries have a diverse seagrass flora (Table 3) there is little comparative data on the extent of seagrass meadows in Indian Ocean countries. This knowledge should be an important priority for regional biodiversity assessment.

2.2 Biodiversity of key taxa among Indian Ocean countries

Species richness is the most commonly used measure of biodiversity, however the degree of endemism and the extent to which some species have restricted ranges is also important. Data is usually only available for groups with broad human interests eg. fish, corals, marine mammals, turtles, cephalopods, seagrass and mangroves. Even among these there is a lack of data, or more usually a lack of comprehensive data, for some countries. We were able to gather comparative data on these better known taxa by country, in the case of coral, mangrove, seagrass and fish species and by region, in the case of shrimps, lobsters, molluscs, marine mammals, turtles and cephalopods. Data presented for individual countries is that of the entire country and not the portion bordering the Indian Ocean in cases such as that of Australia, Indonesia and South Africa where the country's coastal area is across two oceans. For this reason, comparisons must be made with caution as data for the Indian and Pacific oceans include species counts for countries bordering both. Regionalised data was based on two formats, the

NOAA system of Large Marine Ecosystems (LMEs) designed by Sherman¹⁹ as ecological subdivisions of the world's coastal zones and an adaptation of the UNEP Regional Seas system used by Groombridge & Jenkins²⁰.

2.2.1 Coral diversity

Globally, coral reefs comprise little more than 1% of total continental shelf area¹², however they are among the most diverse of the world's ecosystems. There are estimated to be 793 species of scleractinian corals world-wide²¹ of which 719 occur in the Indo-West Pacific region (Table 4). Very few species of any taxa are found in both the Indo-Pacific coral reef area and Caribbean reef area¹³. Figure 1 shows the coral species richness of Indian Ocean rim countries to be similar to those in the Pacific Ocean, with both of these regions having significantly greater coral diversity than the Atlantic. However, countries with large coral diversity such as Indonesia (443), Australia (428) and Thailand (238) border both the Indian and Pacific oceans, thus increasing the apparent diversity of both. Nevertheless, the contribution of the Indian Ocean to this diversity is significant with six other countries spread from Seychelles in the west to India in the north to Malaysia in the east all having over 200 species of coral recorded (Table 2). Both Table 2 and Figure 1 refer to observed and predicted coral species; while those observed refers to the number of scleractinian coral species known to exist according to the UNEP-WCMC database³ based on about 1000 published sources, the predicted number of coral species refers to the maximum expected number of coral species based on GIS database recognising biogeographic regions and coral distribution ranges.

2.2.2 Mangrove diversity

There are 62 known mangrove species²² of which 59 occur in the Indo-West Pacific region (Table 4). Indian Ocean countries with the highest mangrove diversity are Indonesia (45), Australia (39), Malaysia (36) and Thailand (35) (Table 3). Figure 2 shows the highest diversity of mangroves within the Indian Ocean occurs in the eastern region with all countries east of the Maldives, including India, having more than 20 species, while the Maldives and those countries to the west have 10 species or less. Countries bordering the Atlantic Ocean have the lowest diversity of mangroves, with Panama being the only country with more than 10 species (Fig. 2).

Table 2—Coral communities of Indian Ocean rim countries

Country	Coral reef area (km ²)	Coral reefs at risk* (%)	Hard coral sp. (Observed) (no.)	Hard coral sp. (Predicted) (no.)
Australia	48960	32	428	461
Bahrain	570	82	-	68
Bangladesh	50	100	66	-
Comoros	430	99	-	314
Djibouti	450	100	69	325
East Timor	-	-	-	-
Egypt	3800	61	126	318
Eritrea	3260	66	-	333
French Territories:				
Amsterdam Is	-	-	-	-
Crozet	-	-	-	-
Kerguelen	-	-	-	-
Mayotte	-	-	-	313
Reunion	50	100	134	295
Saint Paul	-	-	-	-
India	5790	61	208	345
Indonesia	51020	82	443	602
Iran	700	88	35	68
Iraq	-	-	-	-
Israel	<10	100	145	-
Jordan	<50	75	-	-
Kenya	630	91	200	237
Kuwait	110	93	30	68
Madagascar	2230	87	135	315
Malaysia	3600	91	281	568
Maldives	8920	11	212	244
Mauritius	870	81	161	294
Mozambique	1860	76	194 **	314 **
Myanmar	1870	77	77	277
Oman	530	51	71	128
Pakistan	<50	-	-	-
Qatar	700	66	-	68
Saudi Arabia	6660	60	187	314
Seychelles	1690	17	206	310
Singapore	<100	100	176	186
Somalia	710	95	59	308
South Africa	-	-	43	-
Sri Lanka	680	86	100	318
Sudan	2720	32	106	313
Tanzania	3580	99	194 **	314 **
Thailand	2130	96	238	428
U.A.E.	1190	65	30	68
UK - B.I.O.T.	3770	3	172	329
Yemen	700	73	240	344

* measure of potential threat based on fishing, pollution and sedimentation rather than actual reef state

** for Mozambique and Tanzania combined

Source references: 3, 14

Additional sources for Hard Coral Sp. (Observed): 15, 16, 17

Table 3—Mangrove and seagrass diversity of Indian Ocean rim countries

Country	Mangrove area (km ²)	Mangroves (no. sp.)	Seagrasses (no. sp.)
Australia	11500	39	25
Bahrain	1	-	3
Bangladesh	5767	21	-
Comoros	26	-	4
Djibouti	10	1	2
East Timor	-	-	-
Egypt	861	2	9
Eritrea	581	3	3
French Territories:			
Amsterdam Is	-	-	-
Crozet	-	-	-
Kerguelen	-	-	-
Mayotte	10	-	-
Reunion	-	-	1
Saint Paul	-	-	-
India	6700	28	15
Indonesia	42550	45	13
Iran	207	2	2
Iraq	-	-	-
Israel	0	0	4
Jordan	0	0	-
Kenya	530	8	9
Kuwait	0	0	2
Madagascar	3403	9	10
Malaysia	6424	36	12
Maldives	-	9	2
Mauritius	0.07	2	7
Mozambique	925	10	9
Myanmar	3786	24	2
Oman	10.88	1	-
Pakistan	1683	4	-
Qatar	5	1	1
Saudi Arabia	292	3	6
Seychelles	29	9	8
Singapore	6	31	9
Somalia	910	6	4
South Africa	7	6	3
Sri Lanka	88	23	7
Sudan	937	3	7
Tanzania	1336	10	10
Thailand	2687	35	15
U.A.E.	30	1	1
UK-B.I.O.T.	-	2	1
Yemen	81	2	8

Source references: 3, 5, 18

Table 4—Regionalised species richness of key taxa [Source: ref-3]

	Indo-West Pacific	East Pacific	West Atlantic	East Atlantic
Hard Corals	719	34	62	-
Seagrasses	34	7	9	2
Mangroves	59	13	11	7

2.2.3) Seagrass diversity

Of the 48 known species of seagrasses^{13,20} 34 occur in the Indo-West Pacific region (Table 4). The greatest diversity is found in Australia with over half of these species present (25), although this includes some species that occur on Australia's Pacific coast. Other countries with significant seagrass diversity are India (15), Thailand (15), Indonesia (13) and Malaysia (12). African countries Mozambique, Madagascar and Tanzania have a relatively diverse seagrass flora (9–10 species) (Table 3). Figure 3 shows that the Indian and Pacific oceans have similar levels of seagrass diversity, both with 5 countries having more than 10 species compared to the Atlantic where there are no countries with more than 10 species.

2.2.4) Fish diversity

Species richness of marine fish is highest in the Pacific Ocean (8665 species) compared to 4455 in the Atlantic and 5375 species in the Indian Ocean². Figure 4 shows that the Pacific Ocean has seven countries with more than 1500 species, compared to just two countries in the Atlantic and three in the Indian Ocean (Australia, Indonesia and South Africa). The high number of fish species in Australia (3768) and Indonesia (2741) (Table 5) is coincident with their diverse coral reef systems. Fish species richness is known to be highest in coastal seas¹⁰ and highest associated with reef systems²⁴. Table 5 shows almost half the fish species from Australia and Indonesia to be reef associated. Other Indian Ocean countries with high fish diversity include South Africa (1880), India (1458), Mozambique (1451), the Seychelles (1165), the Maldives (1100) and Malaysia (1029). Sharks have attracted special interest from biogeographers, eg. Groombridge & Jenkins²⁰, and are well represented in the Indian Ocean. Table 6 shows over a quarter of the world's shark species occur in the South African UNEP regional sea and 40% of the world's shark species occur in the East Asian region.

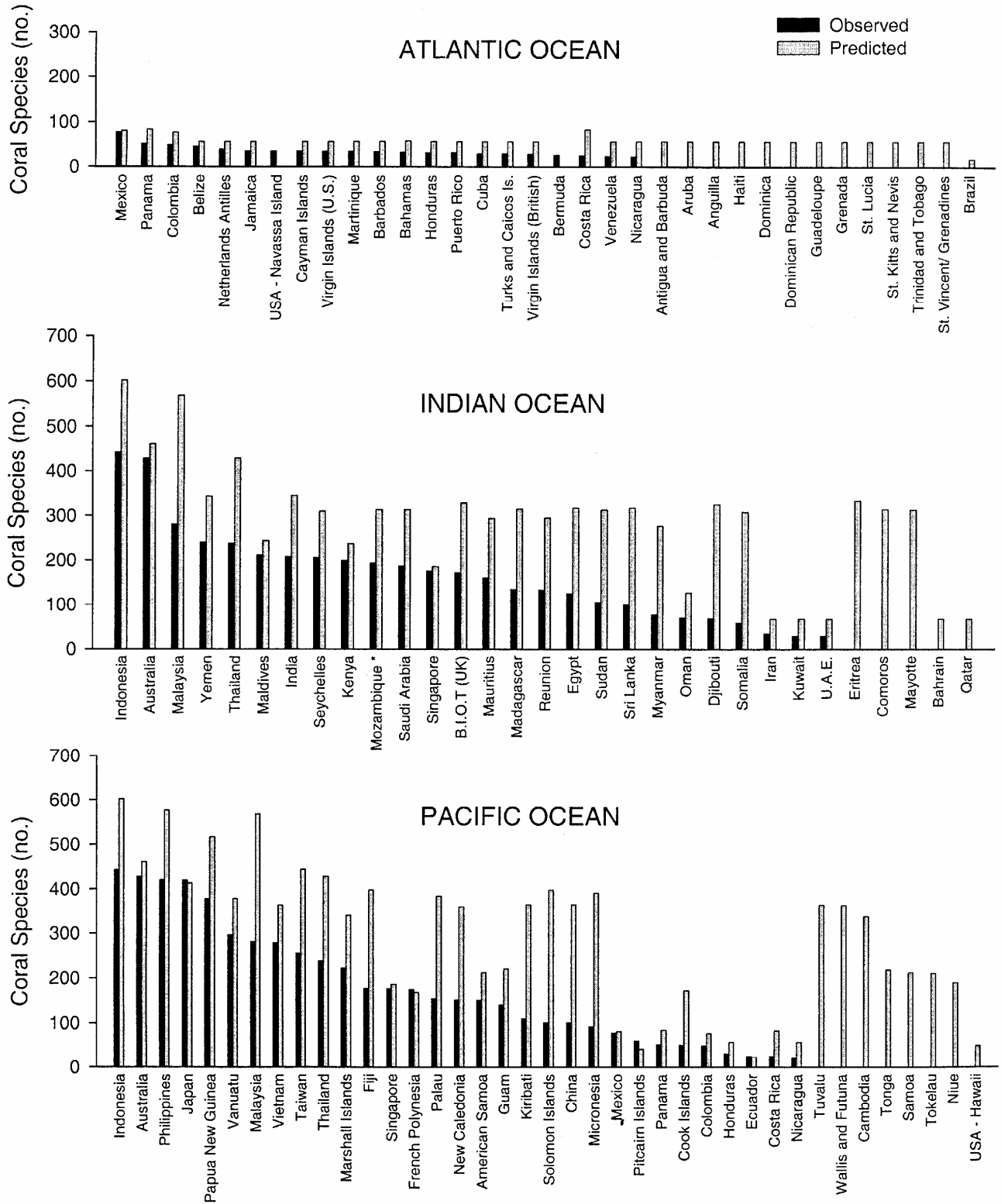


Fig. 1—Observed and predicted coral diversity of individual countries bordering the world’s major oceans [Data source: ref-3, 14]
 *data for Mozambique and Tanzania combined

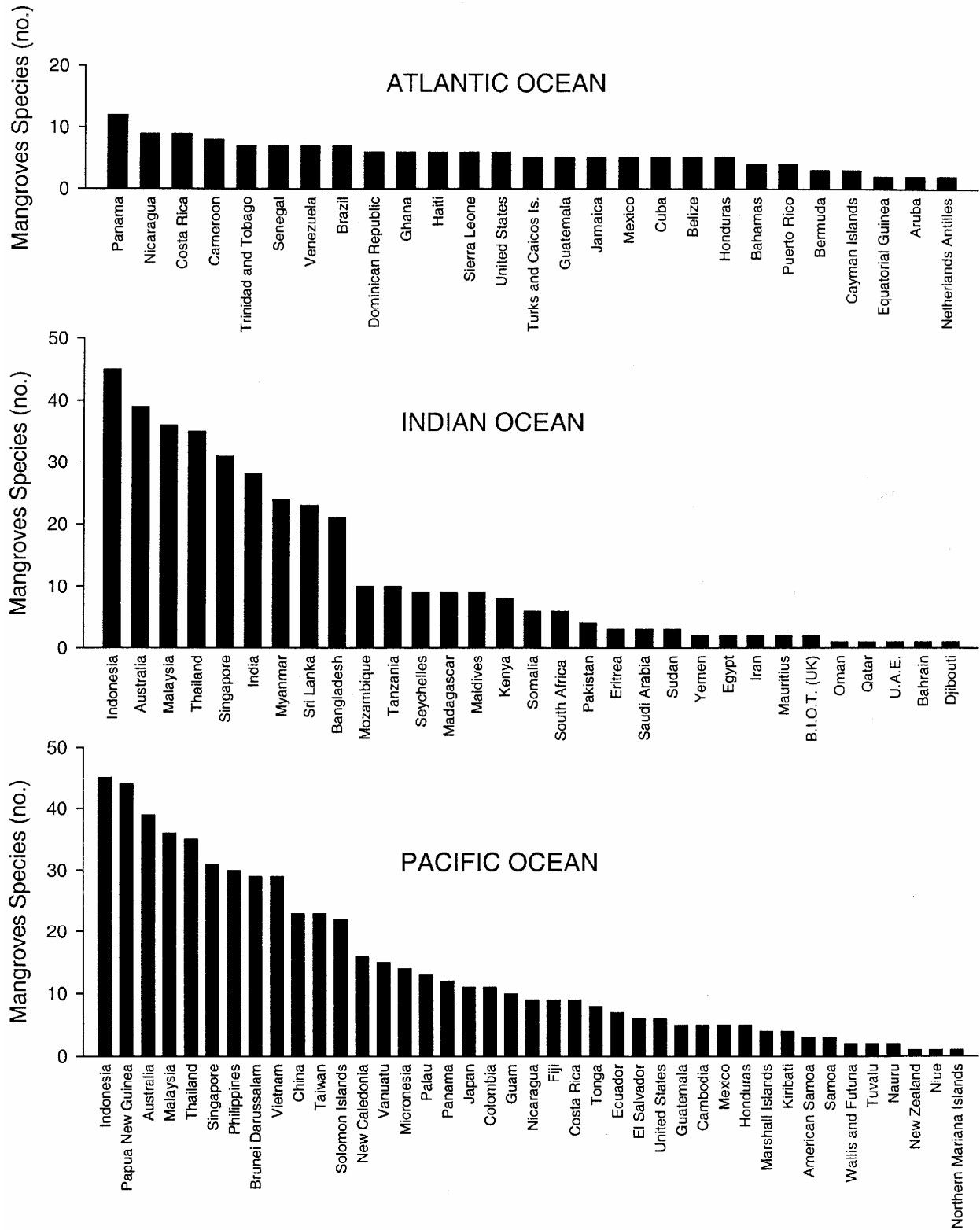


Fig. 2—Mangrove diversity of individual countries bordering the world’s major oceans [Data source: ref-3, 14]

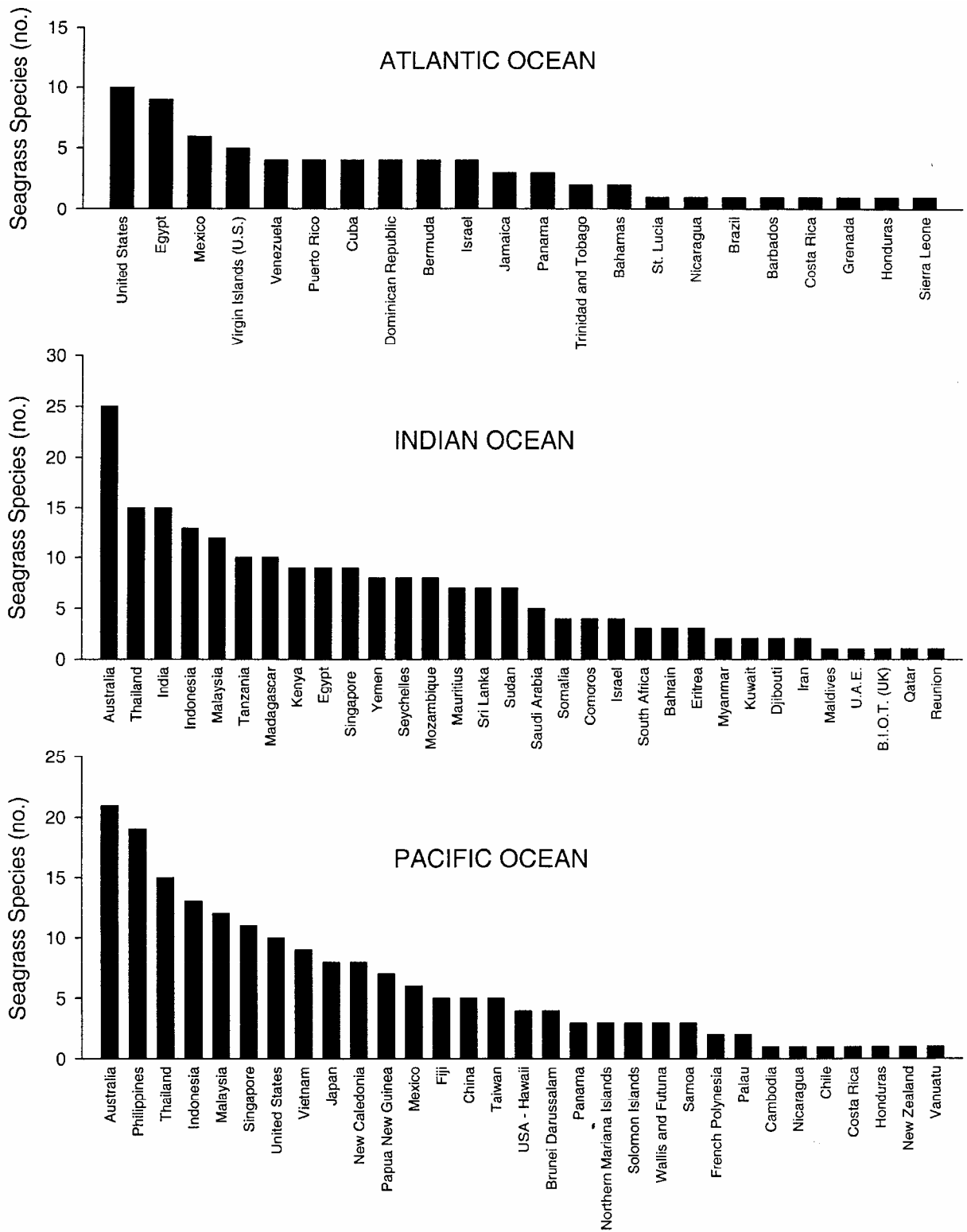


Fig. 3—Seagrass diversity of individual countries bordering the world’s major oceans [Data source: ref-3, 14]

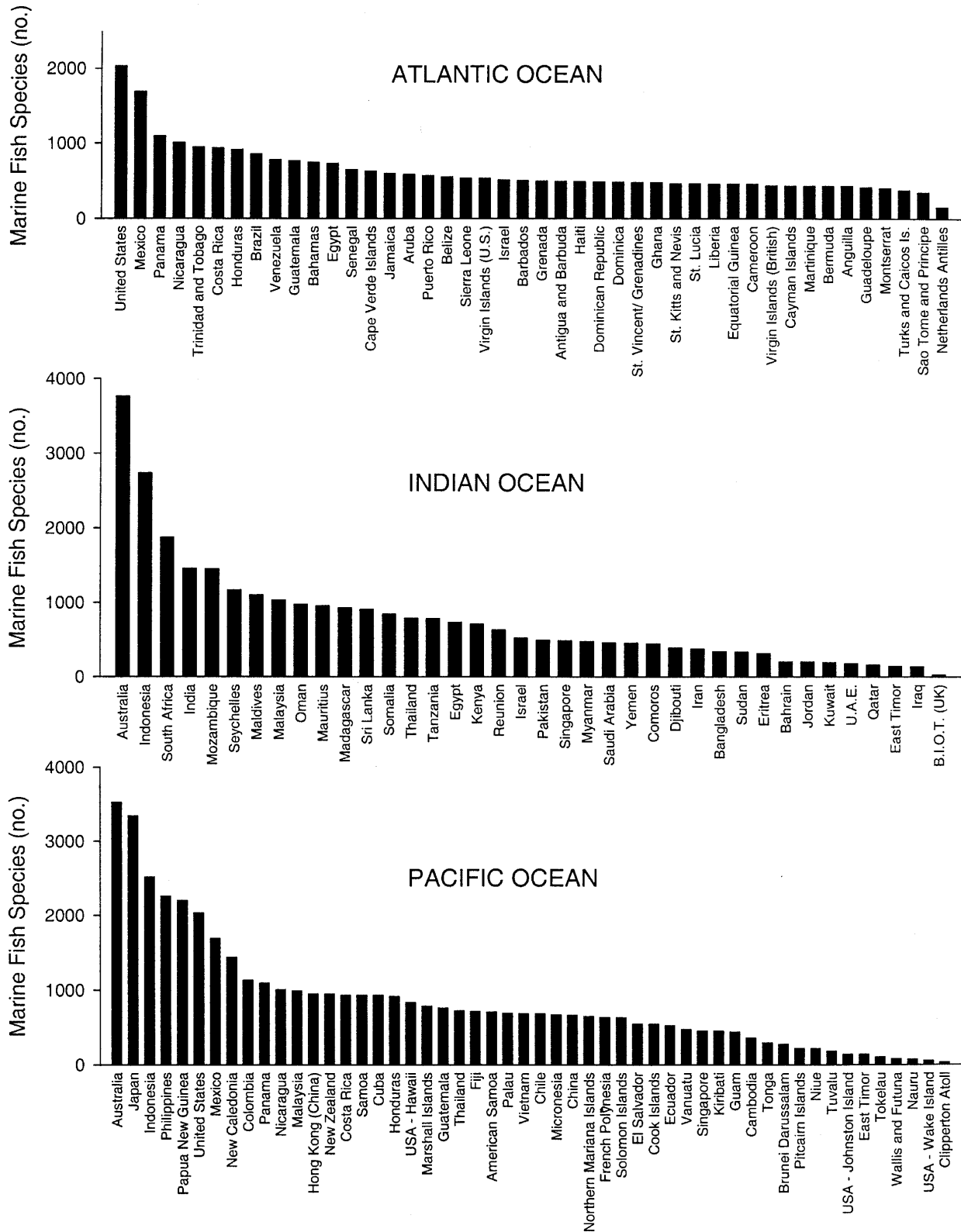


Fig. 4—Marine fish diversity of individual countries bordering the world’s major oceans [Data source: ref-2]

Table 5—Marine and brackish fish diversity of Indian Ocean rim countries [Source ref: 2]

Country	Total no. marine fish sp.	No. reef assoc.	No. pelagic	No. endemic	No. introduced (Questionable)	No. threatened	No. protected
Australia	3768	1531	341	343	8 (24)	86	17
Bahrain	204	74	45	0	0	10	0
Bangladesh	341	81	113	0	(3)	16	0
Comoros	446	294	58	0	0	16	0
Djibouti	391	213	81	0	(3)	26	0
East Timor	143	60	22	0	0	3	0
Egypt	730	354	103	0	7 (4)	47	0
Eritrea	314	171	58	0	1	18	0
French Territories:							
Amsterdam Is	18	1	5	0	0	1	0
Crozet	24	-	2	0	(1)	1	0
Kerguelen	128	-	12	2	(5)	3	0
Mayotte	-	-	-	-	-	-	-
Reunion	629	370	76	4	1 (12)	31	0
Saint Paul	17	1	5	0	0	1	0
India	1458	514	239	11	2 (100)	14	0
Indonesia	2741	1343	328	17	(27)	25	1
Iran	372	114	103	2	2 (1)	19	0
Iraq	139	41	44	0	0	8	0
Israel	521	179	86	0	30	44	1
Jordan	202	109	44	0	0	16	0
Kenya	709	381	106	0	2 (13)	30	0
Kuwait	192	54	49	0	0	9	0
Madagascar	926	467	138	2	2 (25)	46	0
Malaysia	1029	468	186	0	(13)	14	0
Maldives	1100	756	103	2	(14)	25	0
Mauritius	953	608	97	8	1 (30)	41	0
Mozambique	1451	690	153	3	(135)	59	0
Myanmar	474	142	137	0	(5)	23	0
Oman	973	454	133	2	(7)	22	0
Pakistan	494	135	120	1	2 (6)	10	0
Qatar	161	48	45	0	0	8	0
Saudi Arabia	456	237	77	0	(1)	20	0
Seychelles	1165	754	105	1	(66)	36	0
Singapore	485	183	117	0	1 (2)	20	0
Somalia	842	429	133	1	(68)	33	0
South Africa	1880	631	186	49	3 (36)	77	3
Sri Lanka	906	431	143	3	1 (27)	34	0
Sudan	333	208	63	0	1	18	0
Tanzania	781	387	155	0	2 (15)	37	0
Thailand	785	286	177	2	2 (5)	31	0
U.A.E.	182	55	54	0	(1)	9	0
UK-B.I.O.T.	29	17	4	0	0	2	0
Yemen	452	182	87	0	(4)	23	0

2.2.5) Marine mammal and turtle diversity

Cetaceans are well represented in the Indian Ocean (Table 6), with the principally tropical regions having 28-35% of the world's species and the two more southern regions (South Africa, Southwest Australia) having 41% of all known species. There are few pinnipeds in Indian Ocean waters, four species in South Africa and six in South West Australia. One species of sirenian, *Dugong dugon* occurs in all but the South African region. Six of world's 7 known species of turtle are recorded from the Regional Seas making up the Indian Ocean region²⁰. Table 6 shows that the East African (5 species) and East Asian (6 species) regional seas areas are particularly diverse.

2.2.6) Lobster, shrimp and mollusc diversity

Lobsters and shrimps tend to be well known in terms of their taxonomy and distribution as a result of their economic importance. The East Asian seas have the greatest diversity of shrimps with 162 species, which is almost half of all known species.

Additionally, the South Asia area and East Africa area have high shrimp diversity with 94 and 54 species respectively. Similarly the East Asian and East African areas have the highest diversity of lobsters (Table 6). With over 4000 species world-wide²⁰ molluscs are an enormous taxonomic group, and they are well represented in the Indian Ocean.

2.2.7) Cephalopod diversity

Regional assessment on the basis of Large Marine Ecosystems (LMEs) designed by Sherman¹⁹ show species diversity of cephalopods to range from a high of 41 in the Arabian Sea to just 12 in Southwest Australia²⁵. Figure 5 shows the LME's covering the Indian Ocean and a full list of the cephalopod diversity in each LME from east to west is: Agulhas Current (32), Somali Coastal Current (17), Arabian Sea (41), Red Sea (19), Bay of Bengal (31), Indonesia Sea (35), Northern Australian Shelf (14), North West Australian Shelf (16), West Central Australian Shelf (15), South West Australian Shelf (12).

Table 6—Species diversity and endemism in UNEP regional seas of the Indian Ocean [Source ref: 20]

	South African			East African			Red Sea/Aden			Kuwait		
	End.	Sp.	%	End.	Sp.	%	End.	Sp.	%	End.	Sp.	%
Seagrass	0	7	15	0	11	23	0	11	23	0	5	10
Coral genera	0	46	42	0	63	57	0	53	49	1	37	34
Molluscs	0	145	3	0	80	2	0	57	1	0	66	2
Shrimps	0	20	6	0	54	16	0	24	7	0	14	2
Lobsters	2	22	15	2	37	25	0	14	9	0	12	8
Sharks	7	93	27	3	73	21	0	39	11	1	34	10
Cetaceans	0	32	41	0	27	35	0	25	28	0	26	30
Sirenians	0	0	0	0	1	25	0	1	25	0	1	25
Pinnipeds	0	4	12	0	0	0	0	0	0	0	0	0
Turtles	0	2	29	0	5	71	0	3	43	0	4	57
Total	9	371		5	351		0	227		2	199	

	South Asian			East Asian			SW Australian			Indian Ocean Total		
	End.	Sp.	%	End.	Sp.	%	End.	Sp.	%	End.	%	End.
Seagrass	0	9	19	1	17	35	5	17	35	6	13	
Coral genera	1	63	58	4	82	75	0	62	57	6	6	
Molluscs	0	246	6	0	1114	27	0	197	5	0	0	
Shrimps	0	94	27	0	162	47	0	15	4	0	0	
Lobsters	0	23	15	6	48	32	1	10	7	11	7	
Sharks	6	58	17	23	140	40	7	64	18	47	13	
Cetaceans	0	28	32	0	28	32	0	36	41	0	0	
Sirenians	0	1	25	0	1	25	0	1	25	0	0	
Pinnipeds	0	0	0	0	0	0	1	6	18	1	3	
Turtles	0	5	71	0	6	86	0	3	43	0	0	
Total	7	527		34	1598		14	411		71		

End. = number of endemic species
 Sp. = total number of species
 % = percentage of globally known species

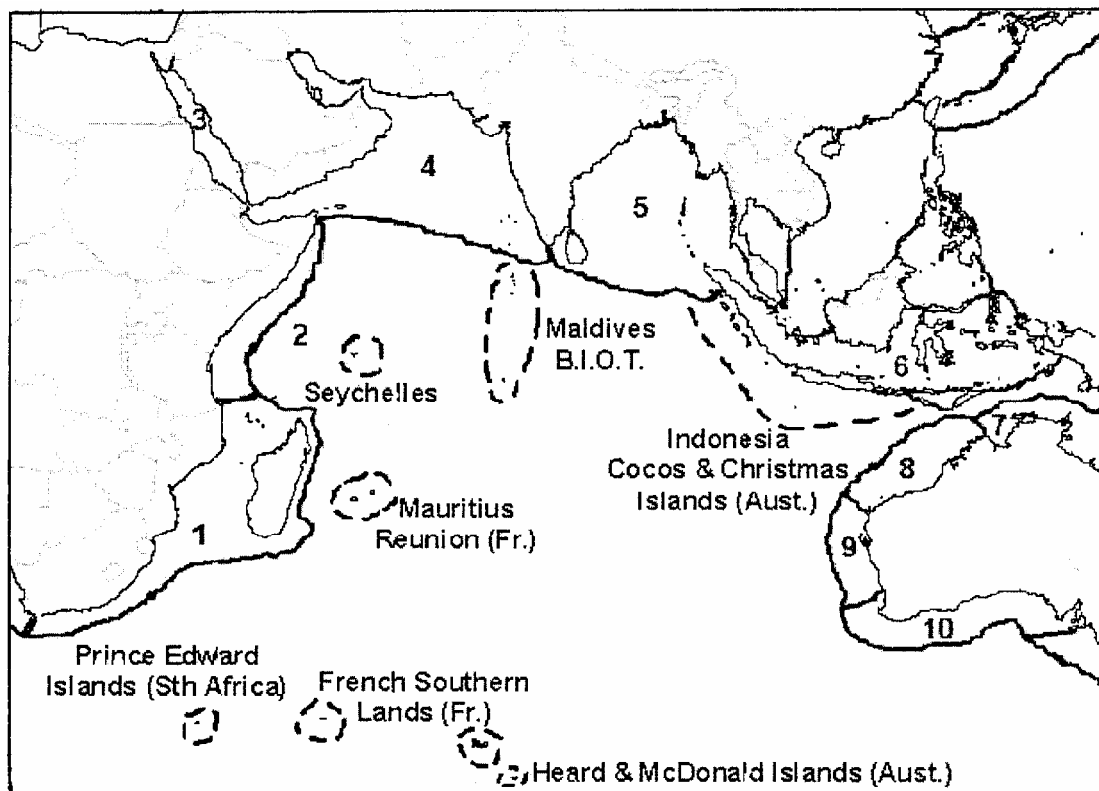


Fig. 5—A proposed approach to Indian Ocean regionalization. Numbered enclosed areas (full lines) indicate existing Large Marine Ecosystems, Areas outlined with dotted lines are those we propose need to be included [Developed with the aid of <http://mapper.edc.uri.edu/website/lmeims/viewer.htm>]

2.3) Endemicity

The extent to which species in the Indian Ocean region are endemic to specific areas and habitats requires greater assessment. This information is greatly lacking and is of particular importance to ensure that adequate conservation measures are in place to protect unique facets of the world's biodiversity. There is some information that suggests the Indian Ocean has a high degree of endemic species. For example, in the Red Sea 90% of some groups of fish are endemic and overall 17% of Red Sea fish are endemic²⁶. Of the taxa whose diversity was compared in Table 6 using the Regional Seas construct of Groombridge & Jenkins²⁰, a total of 71 taxa endemic to regions predominantly in the Indian Ocean were identified. Of these, over half (47) were sharks and species endemic to these regions comprised 13% of all known shark species. Other taxa for which the Indian Ocean is important from the point of view of endemicity are lobsters (11 species comprising 7% of all species), corals (6 genera, 6%) and seagrass (6 species, 13%). The Australian sea lion, *Neophoca cinerea*, is the only sea mammal

endemic to the Indian Ocean. Of the Regional Seas in the Indian Ocean, the East Asian area had the highest number of endemic taxa (34) among those examined by Groombridge & Jenkins²⁰ (Table 6).

Based on coral, reef fish, gastropods and lobsters, 18 global coral reef areas were designated significant due to high endemism²⁷. Ten of these are considered to be "hotspots" on the basis of high threat, facing extreme risk of loss of biodiversity. Five of these ten areas [Sunda Islands (southern Indonesia), Southern Mascarene Islands, Eastern South Africa, Northern Indian Ocean and the Red Sea and Gulf of Aden] are located in the Indian Ocean. These regions are most threatened by coastal and industrial development, global warming, increasing population, pollution and overfishing²⁷.

2.4) Threats to Indian Ocean biodiversity

While only 7-8% of world's ocean area is continental shelf²⁰, it is the area most intensively impacted by humans. The loss of marine biodiversity is highest in coastal areas of the world²⁶. This is particularly so in developing countries and where

there is significant anthropogenic pressure. For example, in several countries there is as much as 57% of the continental shelf area being trawled¹³. The Indian Ocean states have approximately double the population per square kilometre of continental shelf and just 1/10th of the GDP of the Atlantic and Pacific states (Table 1), placing a very great pressure on the coastal regions of the Indian Ocean.

About 40% of the world's offshore oil comes from the Indian Ocean and beach sands, heavy in minerals, are mined in India, South Africa, Indonesia, Sri Lanka and Thailand¹. Heavy maritime transport of petroleum from the Persian Gulf and Indonesia are also important marine activities resulting from mineral and petroleum exploitation in the Indian Ocean¹. Heavy exploitation from the fishing fleets of non Indian Ocean countries (particularly Russia, Japan, South Korea and Taiwan) add to the pressure exerted by countries within the region. Much mangrove habitat has already been lost²⁸ as a result of mangroves being harvested for wood for building material, firewood, animal fodder, fish traps and production of pulp and particle board. Although little research has been done, seagrass habitat loss is also thought to be high due to vessel damage, trawling, dredging, high nutrient and sediment loading¹³. Coral reefs of the Indian Ocean are particularly threatened by land reclamation, coral mining, bleaching, disease and destructive fishing methods.

3) Coastal Marine Biodiversity-The Unknown and Unknowable

Currently the world's biodiversity is estimated at 1.75 million species, excluding microbial species²⁹, but Reaka-Kudla¹¹ estimates a range from 5 to 120 million. Approximately 300 000 marine species are known²⁶ compared with more than 1.5 million known terrestrial species¹². This most likely indicates a lack of knowledge of marine species rather than greater terrestrial diversity as 90% of all Classes are marine³⁰. It is thus evident that most of the world's marine species are unknown, and may remain so given a 500 year projection to describe all species based on a current knowledge of 1.36 million animal species and the possibility that ten times this number actually exist²⁹.

In the Indian Ocean context it is also evident that even many of the better-known taxonomic groups remain poorly known. Using corals as an example (Fig. 1) we can observe, based on modelling of expected coral species distribution according to

Spalding *et al.*³, that it is likely that the diversity of coral species is much greater in many countries than has been recorded in the UNEP-WCMC database which is based on about 1000 published sources. This is likely to be the case for many taxa. Figure 1 shows that in more than half of the Indian Ocean countries, half of the species of corals thought to be present may not have been recorded scientifically. While the source of this data itself is likely to have overlooked some studies in those countries, the overall knowledge of corals and other taxa in many countries is poorly known.

Additionally, we have observed that just describing the extent of different habitat types as a first step to estimating the extent of biodiversity will require much work and should be a priority. Coastal habitats are generally small and being submerged are difficult to assess with coarse scale global sensors often used for terrestrial ecosystems. High resolution remote sensing capabilities are improving rapidly but not yet widely applied¹³. High resolution mapping is doubtful, expensive and has not been attempted globally¹³.

Much of the knowledge of marine biodiversity is measured by species richness, however this may not be best estimate of total diversity as it does not account for the fact that organisms that differ widely lead to greater diversity than species that are very similar. There is a large gap in current knowledge with respect to biodiversity assessment outside the scope of species numbers. Biodiversity can also be described in terms of functional, ecological and genetic diversity³¹. Functional, or morphological, diversity can be based on similar functions such as feeding type or reproductive method³², by the range of functions an organism performs in a system²⁶ or in terms of trophic levels¹³. Genetic diversity refers to the variation in genetic information within or between individuals of a population, species or community; this includes gene, genome and population diversity¹³. Genetic diversity can change due to chromosomal mutation, physical or behavioural isolation, natural selection or genetic drift^{26,32}. Commercial fishing concentrating on particular size ranges alters genetic composition³³. Finally, assessment of species assemblage may prove valuable as measure of ecosystem condition, however presently not enough is known about marine species and habitats for this type of evaluation.

It goes without saying that it is impossible to know what attributes of the Indian Ocean's biodiversity

have already been altered or lost as a result of human interference to coastal habitats. For example mangrove habitats harbour much of the world's tropical biodiversity and Kelleher *et al.*²⁸ estimated that 50% of the world's mangrove forests have been lost as a result of clearing and alteration of coastlines. Rather than become despondent about this, it is important to begin to characterise existing patterns of habitat distribution and abundance, protecting a representative set of these habitats in each bioregion from threatening processes, and then use these areas as the basis for increasing our understanding of actual biodiversity.

We may of course never know the full extent of biodiversity in any of the world's oceans and the rate at which we increase our understanding is likely to be the lowest in the Indian Ocean. The impacts of climate change will alter coastal marine ecosystems affecting the range of species and their ecology at a rate faster than we can begin to record them. Our only chance to make progress on this is to understand species, habitat and ecosystem responses to natural climate variability and to infer from this the likely patterns of change and adaptation as a result of climate change.

4) A Framework for Improved Knowledge of Indian Ocean Biodiversity Linked to Biodiversity Conservation

There is an opportunity for the Indian Ocean region countries to take a lead in increasing knowledge and understanding of the coastal biodiversity of the region. We need to make progress towards adequately conserving biodiversity by protecting and/or sustainably managing habitats representative of the ecosystems that make up the region.

We propose that the steps to achieve these goals can be as follows:

- Establishing an agreed Indian Ocean bioregionalisation on which to base biodiversity assessments
- Thorough synthesis of existing information on a bioregional basis into an accessible well managed database (preferably using existing web based tools)
- A biodiversity "gap" analysis (both geographic and taxonomic) that identifies areas of the least knowledge and prioritises them (perhaps according to degree of current threat) for biodiversity assessment projects

- Undertaking these targeted assessment programs according to priority and available sources of funding.
- Linking efforts to assess biodiversity to established conservation programs such the UNEP Regional Seas Program or the IUCN global system of representative protected areas as well as the initiatives of individual countries.

The first three of these steps could be conducted as part of an international collaborative project, perhaps coordinated by IOGOOS and conducted in association with international programs such as UNEP. The fourth step could also consist of internationally collaborative projects coordinated by IOGOOS and conducted in association with other international programs of the UNEP, IOC, CoML, World Fish and FAO.

4.1) Current approaches to Indian Ocean coastal bioregionalisation

A system of Large Marine Ecosystems (LME) was designed by Sherman¹⁹ as ecological subdivisions of the world's coastal zones. These LMEs are coastal areas from river basins and estuaries to the seaward boundaries of continental shelves and the outer margins of the major current systems. They are relatively large regions, 200,000 km² or greater, characterised by distinct bathymetry, hydrography, productivity, and trophically dependent populations. The LME system adopted by NOAA³⁴ has 64 LMEs and the system is supported by the World Conservation Union (IUCN), the Intergovernmental Oceanographic Commission of UNESCO (IOC), other United Nations agencies and the US National Oceanic and Atmospheric Administration (NOAA). The Large Marine Ecosystems covering the Indian Ocean region (Fig. 5) are the Agulhas Current, Somali Coastal Current, Red Sea, Arabian Sea, Bay of Bengal, Indonesian Sea, North Australian Shelf, North West Australian Shelf, West Central Australian Shelf and South West Australian Shelf. The Indonesian Sea and North Australian Shelf areas are also considered to be part of both the Indian and Pacific oceans.

The other regionalisation relevant to the Indian Ocean is the UNEP system of Regional Seas³⁵ that promotes regional agreements and regional programs to address issues of marine environmental management and protection. The UNEP Regional Seas Program has a number of action plans that cover

some but not all the Indian Ocean region. Groombridge & Jenkins²⁰ used an adaptation of the regional seas approach in assessing patterns of marine biodiversity and include a useful discussion on the overlap between the Regional Seas coverage of the world's oceans and that of the LME approach.

4.2) Proposed bioregionalisation for the Indian Ocean

An obstacle to understanding the biodiversity of coastal seas of the Indian Ocean region is that many of the databases collect the data by country. This means that information for countries such as Australia, Malaysia, Thailand, Indonesia and South Africa may not be readily separated into their Indian, Pacific, Atlantic and Southern oceans components. A similar problem exists in assigning data collected by country into bioregions where some countries straddle two bioregions (e.g., India, in the case of the LME system). These problems can be overcome by going back to the original data sources, however this would be best done once an agreed regionalisation for the Indian Ocean is in place.

While we do not advocate any particular approach because this needs to be developed through a collaborative and consultative process that will require the involvement of specialists from each country, we do believe that the LME System presents a useful starting point on which to base discussion. Figure 5 outlines the LMEs, which cover the Indian Ocean, and also indicates some important areas not captured by the LME system. Any revised bioregionalisation for the Indian Ocean should also consider the open ocean areas not covered by the existing system. Whatever regionalisation design is adopted, it should be able to support international efforts to protect biodiversity through a global representative system of marine protected areas²⁸, which continues to be pursued by the IUCN and other government and non-government organisations around the world.

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