Appendix 2-D. Structure and distribution of coastal fish habitats and changes projected by IPCC

The coastal ecosystems of the Pacific Island region include a diversity of predominantly coral reef habitats subject to a range of environmental influences, such as exposure to freshwater inflow, water temperature, depth and currents. These determine the structure, function and extent of these ecosystems and the diversity and abundance of associated fish and invertebrates. In addition, many countries in the region have mangrove and seagrass habitats often associated with coral reefs to varying degrees. Inter-tidal flats comprised of soft sediments with a rich interstitial fauna and flora are also a common feature of coastal ecosystems throughout the region. This section presents a summary of the coastal habits found in the 14 GCF participating countries and projected future changes to these habitats as a consequence of climate change.[1]

Coral reefs

Coral reefs are a cornerstone of the region's coastal fisheries supporting small scale fishing operations that provide sustenance and income. The extent of coral reefs analysed from Landsat 7 high resolution (30 m) remote sensing images, and the information from the *Atlas of Pacific Ocean Coral Reefs*, provide information on the extent, structure and distribution of the various types of coral reefs in the Pacific Islands region.[2,3] For several PICs in Micronesia and Polynesia, the areas of coral reef habitat greatly exceed the area of land (1).

Coral reefs are the best studied coastal habitat, covering over 69,000 km^2 in the Pacific Islands region covering countries and territories.[4] An assessment of their status and trends in the region,[5] focused on two indicators – live hard coral cover and macroalgae cover. Based on 440,000 observations since 1987 across the Pacific Islands region, results show that prior to 1998, average hard coral cover was relatively high and stable between 37.0% and 37.7%. In 2019 this had declined to 31.3%. The impacts of the 1998 El Niño in the Pacific Islands region were evident in a 2.3% decline in average coral cover between 1999 and 2001, and El Niño events in 2015 and 2016 caused considerable coral mortality across the region, which was apparent in the 2.7% decline in average coral cover between 2015 and

---

[1] Much of the foundational material for this Section was drawn from the following two publications: Hoegh-Guldberg, O., Andréfouët, S., Fabricius, K.E., Diaz-Pulido, G., Lough, J.M. Marshall, P.A. and Pratchett, M.S. Vulnerability of coral reefs in the tropical Pacific to climate change. In: Bell J.D., Johnson, J.E. and Hobday, A.J. 2011. Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Chapter 4. pp. 251–296. Secretariat of the Pacific Community, Noumea, New Caledonia. 941 pages, and Waycott, M. McKenzie, L.J. Mellors, J.E. Ellison, J.C. Sheaves, M.T., Collier, C. Schwarz, A-M., Webb, A., Johnson, J.E. and Payri, C.E. 2011. Vulnerability of mangroves, seagrasses and intertidal flats in the tropical Pacific to climate change. In: Bell J.D., Johnson, J.E. and Hobday, A.J. 2011. Vulnerability of tropical Pacific fisheries and aquaculture to climate change. pp. 311–368. Secretariat of the Pacific Community, Noumea, New Caledonia. 941 pages.

[2] Andréfouët, S., Chauvin, C., Kranenburg, C., Muller-Karger, F. and Noordeloos, M. 2006. Atlas of Southeast Papua New Guinea Coral Reefs. Institut de Recherche pour le Développement, Nouméa, Nouvelle-Calédonie.

[3] Andréfouët, S., Chauvin, C. and Kranenburg, C. 2009. Atlas of Pacific Ocean Coral Reefs. Institut de Recherche pour le Développement, Nouméa, Nouvelle-Calédonie.

[4] Souter D., Planes S., Wicquart J., Logan M., Obura D., Staub F. (Eds) (2021a) Status of Coral Reefs of the World: 2020 Report. Global Coral Reef Monitoring Network (GCRMN) and International Coral Reef Initiative (ICRI). DOI: 10.59387/WOTJ9184

[5] Souter D., Planes S., Wicquart J., Logan M., Obura D. and Staub F. (Eds). 2021a. *Status of Coral Reefs of the World: 2020 Report*. Global Coral Reef Monitoring Network (GCRMN) and International Coral Reef Initiative (ICRI). DOI: 10.59387/WOTJ9184

2017. The average cover of macroalgae on the other hand remained relatively low (15%) and stable between 1987 and 1999, followed by a progressive increase over the last two decades, peaking at 20.8% in 2018.[6]

At the apex of the hierarchy, the coral reefs of the region can be divided into 'continental' and 'oceanic' reefs.[7] Continental reefs are defined by the geological origin of their underlying substrates, or the size of associated land masses, and are found only in Papua New Guinea and Fiji (on Viti Levu and Vanua Levu). All other coral reef areas in PICs are considered to be oceanic.

Both continental and oceanic reefs include barrier reefs, fringing reefs, and patch reefs. However, the oceanic barrier, fringing and patch reefs are all attached to oceanic island reef complexes, whereas the continental barrier, fringing and patch reefs are attached to the continent. As a sub-level in the hierarchy of continental reefs, continental islands and their associated reefs may also occur in close proximity to the continent (e.g. found elsewhere in the region such as in the Belep Islands in New Caledonia).

Atolls and banks are distinguished mainly by the presence/absence of a closing rim, and the degree to which their lagoons are closed. Islands differ from atolls and banks in that the land mass is not derived from carbonate sediments. Fringing reefs form around islands and continental masses and vary in the way they are exposed to oceanic swells or positioned in lagoons and embayments.

Barrier reefs are offshore structures, separated from the land by lagoons or large sedimentary terraces. Patch reefs are intertidal or subtidal constructions of varying sizes, which are not continuous (like barrier reefs) or adjacent to land (like fringing reefs). These broad reef types can be divided into finer levels (classes) of reef geomorphology, exposure and depth.[8]

Several PICs consist almost entirely of atolls (e.g. Marshall Islands, Kiribati and Tuvalu) (Table 1). Oceanic reef structures in some PICs are dominated by fringing reefs directly exposed to ocean waves and runoff from high island land masses (e.g. Vanuatu). Most of the PICs with oceanic reefs, however, have a range of islands, banks and atolls of various sizes (e.g. Federated States of Micronesia (FSM), Palau and Niue).

At the finest level (class) of reef geomorphology, there is great variation among PICs, ranging from two classes of reef type in Nauru to up to > 150 classes in Fiji and PNG (Table 1).[9] This diversity of reef types is significant for PICs because the various categories and classes of reef differ in their exposure and sensitivity to disturbance, and presumably also to the effects of climate change.

---

[6] Souter D., Planes S., Wicquart J., Logan M., Obura D. and Staub F. (Eds). 2021a. *Status of Coral Reefs of the World: 2020 Report*. Global Coral Reef Monitoring Network (GCRMN) and International Coral Reef Initiative (ICRI). DOI: 10.59387/WOTJ9184

[7] Hoegh-Guldberg, O., Andréfouët, S., Fabricius, K.E., Diaz-Pulido, G., Lough, J.M. Marshall, P.A. and Pratchett, M.S. Vulnerability of coral reefs in the tropical Pacific to climate change. In: Bell J.D., Johnson, J.E. and Hobday, A.J. 2011. Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Chapter 4. pp. 251–296. Secretariat of the Pacific Community, Noumea, New Caledonia. 941 pages.

[8] Andréfouët, S., Cabioch, G., Flamand, B. and Pelletier, B. 2009. A reappraisal of the diversity of geomorphological and genetic processes of New Caledonian coral reefs: A synthesis from optical remote sensing, coring and acoustic multibeam observations. *Coral Reefs* 28, 691–707.

[9] Hoegh-Guldberg, O., Andréfouët, S., Fabricius, K.E., Diaz-Pulido, G., Lough, J.M. Marshall, P.A. and Pratchett, M.S. Vulnerability of coral reefs in the tropical Pacific to climate change. In: Bell J.D., Johnson, J.E. and Hobday, A.J. 2011. Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Chapter 4. pp. 251–296. Secretariat of the Pacific Community, Noumea, New Caledonia. 941 pages.

The degree to which atolls are 'closed' is a significant feature. The closed to semi-closed atolls found in the central Pacific Ocean differ from the open atolls of the western Pacific Ocean in their exposure and sensitivity to hydrodynamic change. Hydrodynamic regimes and average residence times of water in lagoons can easily be modified by sea level and wind/wave variations on short time-scales, and presumably also by slowly shifting conditions.[10,11] Changes that switch semi-closed lagoonal waters from being replenished rapidly to being renewed slowly have led to planktonic algal blooms, anoxia and mass mortalities of fish and invertebrates.[12,13]

Table 1. Total area (km^2) of land and coral reef, and areas of coral reef comprising atolls, banks and formations associated with islands, for Pacific Island countries.Values derived from Landsat 7 images and 'Atlas of Pacific Ocean Coral Reefs', and from Institut de Recherche pour le Developpement. The number of reef classes for each PIC is also shown.[14]

PIC	Land	Total reef	Atoll[a]	Bank	Island				No reef classes
					Barrier reef	Patch reef	Fringing reef	Inter-reefal	
Melanesia									
Fiji	18,272	25,666	n/a	n/a	n/a	n/a	n/a	n/a	>150
PNG	462,243	27,086	n/a	n/a	n/a	n/a	n/a	n/a	>150
Solomon Islands	27,556	8,535	2,191	599	1,471	645	1,328	2,301	134
Vanuatu	11,880	1,244	22	40	59	28	629	466	58
Micronesia									
FSM	700	15,034	11,859	420	523	21	212	2,039	72
Kiribati	690	4,320	3,986	114	-	-	-	-	23
Marshall Islands	112	13,930	13,910	20	-	-	-	-	20
Nauru	21	7	7	-	-	-	-	-	3
Palau	494	2,496	555	17	615	86	163	1,060	58
Polynesia									
Cook Islands	240	667	548	5	58	1	17	38	37
Niue	259	56	56	-	-	-	-	-	9
Samoa	2,935	466	-	-	203	7	139	117	28
Tonga	699	5,811	47	96	564	377	171	4,556	70
Tuvalu	26	3,175	3,040	135	-	-	-	-	18

* estimate only. a = area below high water mark including drowned atolls. b = small area below high water mark including drowned banks. c = includes lagoons and sedimentary areas within main island reef types. n/a = data is not available.

Island size also affects the exposure of reefs to disturbance. Barrier reefs on large islands and continental land masses are more likely to be exposed to plumes of sediments from rivers, compared with barrier reefs on small islands. Similarly, fringing reefs surrounding large land masses are more likely to be affected by floods and rainfall than barrier reefs.

---

[10] Tartinville, B., Deleersnijder, E. and Rancher, J. 1997. The water residence time in the Mururoa atoll lagoon: Sensitivity analysis of a three-dimensional model. *Coral Reefs* 16, 193–203. 290

[11] Kraines, S., Suzuki, A., Yanagi, T., Isobe, M. and others. 1999. Rapid water exchange between the lagoon and the open ocean at Majuro Atoll due to wind, waves and tide. *Journal of Geophysical Research-Oceans* 104, 15,635–15,654.

[12] Adjeroud, M., Andréfouët, S. and Payri, C. 2001. Mass mortality of macrobenthic communities in the lagoon of Hikueru atoll (French Polynesia). *Coral Reefs* 19, 287–291.

[13] Dufour, P., Andréfouët, S., Charpy, L. and Garcia, N. 2001. Atoll morphometry controls lagoon nutrient regime. *Limnology and Oceanography* 46, 456–461.

[14] Adapted from Hoegh-Guldberg, O., Andréfouët, S., Fabricius, K.E., Diaz-Pulido, G., Lough, J.M. Marshall, P.A. and Pratchett, M.S. Vulnerability of coral reefs in the tropical Pacific to climate change. In: Bell J.D., Johnson, J.E. and Hobday, A.J. 2011. Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Chapter 4. pp. 251–296. Secretariat of the Pacific Community, Noumea, New Caledonia. 941 pages.

Overall, the location, spatial organisation and fragmentation of coral reefs influence their resilience to perturbations. In particular, reefs on small, isolated islands are less likely to be resilient than those on well-connected islands that receive larval coral recruits from a variety of sources. On larger islands, the main threats to the resilience of coral reefs are land-based sediments and pollution.

Regardless of reef size, type and orientation, the location of a reef can also be expected to influence the extent of disturbances. Reefs located at depths of 30 m or more are unlikely to be severely affected by increases in SST, severe storms or changes in sea level but will be affected by changes in pH levels, available calcium and aragonite levels. Such reefs occur commonly between Tuvalu and FSM. Reef crests located in places flushed by oceanic waters often fare better than enclosed basin or lagoonal reef areas during periods of high SST associated with mass coral bleaching events.[15]

The location of reef classes within reef types also determines exposure and sensitivity. For example, because the fore-reef receives the greatest amount of wave energy, the corals there grow faster due to the high rate of water movement, and hence nutrient and gas exchange. Differences in light intensity can also have large influences on the extent of coral bleaching and mortality[16,17] with high islands sometimes 'shading' coral reefs and reducing stress.[18]

Reef flats and terraces are usually sheltered from wave action and support conditions suitable for growth of diverse coral communities. However, reef flats, shallow fore-reefs, and reticulated areas are more susceptible to physical destruction by tropical cyclones than deep areas of fore-reefs and lagoons.[19] Also, reef crests and high energy reef flats create environments conducive for crustose coralline algae, which are susceptible to changes in the pH of sea water.[20]

In summary, reef types and classes differ in their exposure and sensitivity to disturbance, often depending on their location. Consequently, PICs with a large variety of reef structures and types are likely to cope better with the effects of climate change than those with a limited diversity of reefs.

Mangroves

Mangrove forests occur on sediments associated with low-energy shorelines, between mean low-tide and high-tide levels. Mangroves have evolved to tolerate saline sediments and inundation by sea water, with different species displaying a range of tolerance. This variability in tolerance to saline conditions contributes to patterns of species distribution across the intertidal zone.

---

[15] Nakamura, T. and Van Woesik, R. 2001. Water-flow rates and passive diffusion partially explain differential survival of corals during the 1998 bleaching event. *Marine Ecology Progress Series* 212, 301–304.

[16] Hoegh-Guldberg, O. 1999. Climate change, coral bleaching and the future of the world's coral reefs. *Marine and Freshwater Research* 50, 839–866.

[17] Mumby, P.J., Chisholm, J.R.M., Edwards, A.J., Andréfouët, S. and Jaubert, J. 2001. Cloudy weather may have saved Society Island reef corals during the 1998 ENSO event. *Marine Ecology Progress Series* 222, 209–216.

[18] West, J. and Salm, R. 2003. Resistance and resilience to coral bleaching: Implications for coral reef conservation and management. *Conservation Biology* 17, 956–967

[19] Harmelin-Vivien, M. 1994. The effects of storms and cyclones on coral reefs: A review. In: Finkl, C.H.F. (Ed.) Coastal hazards: Perception, susceptibility and mitigation. Coastal Education and Research Foundation, Charlottesville, United States of America, pp. 211–231.

[20] Kuffner, L.B., Andersson, A.J., Jokiel, P.L., Rodgers, K.S. and Mackenzie, F.T. 2008. Decreased abundance of crustose coralline algae due to ocean acidification. *Nature Geoscience* 1, 114–117.

There is an estimated 6,000 km^2 of mangroves in the Pacific Islands region,[21] representing approximately 3.8% of the world's mangrove forests;[22] the smallest area of mangrove forests worldwide. The largest areas are in Fiji, New Caledonia, PNG, and Solomon Islands. While some areas of mangroves are diverse and assessed to be in relatively good condition, other locations only have remnant forests left due to infrastructure development (e.g. the airport in Pohnpei, Federated States of Micronesia) is located on a low-lying mangrove island) and reclamation (e.g. in Fiji mangrove forest area is estimated to have declined from 42,462 ha in 1999 to 37,000 ha in 2009 largely due to land reclamation).[23] Across many PICs mangroves have been observed to migrate landward as a natural response to rising sea level. In cases where this natural landward migration is constrained by topography or the presence of seawalls and other man-made structures, mangrove areas reduce over time, with continued sea level rise and other climate change impacts threatening mangroves into the future.[24]

Since the 1970s, the decline of coastal habitats has accelerated globally, including in the Pacific Islands region.[25,26,27] This is due to poor land management and delivery of terrestrial pollutants, coastal development, increased sedimentation from coastal catchments, and destructive and illegal fishing.[28,29,30] Climate change, however, is now the strongest driver affecting coastal habitats, through higher sea temperatures and marine heatwaves, sea level rise, ocean acidification, more intense storms and cyclones, El Niño Southern Oscillation (ENSO) events, and the synergistic effects

---

[21] https://www.globalmangrovewatch.org/

[22] Senilolia H., Skelton P.A., Tuiwawa M.V. 2014. A field guide to the mangrove and seagrass species of Fiji. USP Press, Suva, Fiji.

[23] Ellison J. and Fiu M. 2010. Vulnerability of Fiji's mangroves and associated coral reefs to climate change. Review for the World Wildlife Fund. University of Tasmania, Launceston, Australia.

[24] Veitayaki J., Waqalevu V., Varea R. and Rollings, N. 2017. Mangroves in small island development states in the Pacific: An overview of a highly important and seriously threatened resource. Participatory Mangrove Management in a Changing Climate: Perspectives from the Asia-Pacific, 303-327.

[25] Albert S., Saunders M.I., Roelfsema C.M., Leon J.X., Johnstone E., Mackenzie J.R., Hoegh-Guldberg O., Grinham A.R., Phinn S.R., Duke N.C., Mumby P.J., Kovacs E. and Woodroffe C.D. 2017. Winners and losers as mangrove, coral reef and seagrass ecosystems respond to sea-level rise in Solomon Islands. *Environmental Research Letters*, 12(9), p.094009.

[26] Guannel G., Arkema K., Ruggiero P. and Verutes G. 2016. The Power of Three: Coral Reefs, Seagrasses and Mangroves Protect Coastal Regions and Increase Their Resilience. Plos One 11, e0158094.

[27] Hassenruck C., Hofmann L.C., Bischof K. and Ramette A. 2015. Seagrass biofilm communities at a naturally CO2-rich vent. *Env Microbiol Rep* 7, 516-525.

[28] Veitayaki J., Waqalevu V., Varea R. and Rollings N. 2017. Mangroves in small island development states in the Pacific: An overview of a highly important and seriously threatened resource. Participatory Mangrove Management in a Changing Climate: Perspectives from the Asia-Pacific, 303-327.

[29] Johnson, J.E., Allain, V., Basel, B., Bell, J.D., Chin, A., Dutra, L.X.C., Hooper, E., Loubser, D., Lough, J., Moore, B.R. and Nicol, S. 2020. Chapter 10: Impacts of climate change on marine resources in the Pacific Island region. In: *Climate Change Impacts in the Pacific*, Lalit Kumar (Editor), Springer, Cham.

[30] Dutra L.X.C., Haywood M.D.E., Singh S., Ferreira M., Johnson J.E., Veitayaki J., Kininmonth S., Morris C.W. and Piovano, S. 2021. Synergies between local and climate-driven impacts on coral reefs in the Tropical Pacific: A review of issues and adaptation opportunities. Marine Pollution Bulletin, 164: 111922

between drivers.[31,32,33] These impacts are accelerating as the climate continues to change and are expected to continue to degrade the condition of coastal habitats.[34]

The mangrove composition of the tropical Pacific Ocean is extremely diverse – 31 of the 70 species recognised globally are found in the region, including five hybrids. The largest number of species occurs in PNG (Table 2), which is the country with the greatest diversity of mangroves in the world.[35] The diversity of mangroves decreases progressively from west to east across the region, with only four species and one hybrid occurring in Samoa. Further east, in French Polynesia, the single species of Rhizophora is likely to have been introduced [36,37] and has proliferated on all the high islands of the Society archipelago.[38]

Table 2. Number of seagrass and mangrove species reported for each country.[39]

Country	Number of seagrass species	Number of mangrove species (hybrid)
Cook Islands	0	0
Federated States of Micronesia	10	15(1)
Fiji	6	7(1)
Kiribati	2	4
Marshall Islands	3	5
Niue	0	1
Nauru	0	2
Palau	11	14(3)
Papua New Guinea	13	31(2)
Samoa	5	3
Solomon Islands	10	17(2)
Tonga	4	7
Tuvalu	1	2
Vanuatu	11	14(3)

[31] Aronson R.B. and Precht W.F. 2016. Physical and Biological Drivers of Coral-Reef Dynamics. Coral Reefs World 6, 261-275.

[32] Souter D., Planes S., Wicquart J., Logan M., Obura D. and Staub F. (Eds) 2021b. Status of Coral Reefs of the World: 2020 Report. Chapter 9. Status and trends of coral reefs of the Pacific region. Global Coral Reef Monitoring Network (GCRMN) and International Coral Reef Initiative (ICRI).

[33] Johnson, J.E., Allain, V., Basel, B., Bell, J.D., Chin, A., Dutra, L.X.C., Hooper, E., Loubser, D., Lough, J., Moore, B.R. and Nicol, S. 2020. Chapter 10: Impacts of climate change on marine resources in the Pacific Island region. In: *Climate Change Impacts in the Pacific*, Lalit Kumar (Editor), Springer, Cham.

[34] Dutra L.X.C., Haywood M.D.E., Singh S., Ferreira M., Johnson J.E., Veitayaki J., Kininmonth S., Morris C.W. and Piovano, S. 2021. Synergies between local and climate-driven impacts on coral reefs in the Tropical Pacific: A review of issues and adaptation opportunities. Marine Pollution Bulletin, 164: 111922

[35] Ellison, J.C. 2009. Wetlands of the Pacific Island region. *Wetlands Ecology and Management* 17, 169–206.

[36] Taylor, F.J. 1979. Rhizophora in the Society Islands. *Pacific Science* 33, 173–176.

[37] Iltis, J. and Meyer, J-Y. 2010. La mangrove introduite dans les archipels éloignés d'Océanie, entre assimilation et rejet. *L'Espace Géographique* 3, 267–275.

[38] Iltis, J. and Meyer, J-Y. 2010. La mangrove introduite dans les archipels éloignés d'Océanie, entre assimilation et rejet. *L'Espace Géographique* 3, 267–275.

[39] Waycott, M. McKenzie, L.J. Mellors, J.E. Ellison, J.C. Sheaves, M.T., Collier, C. Schwarz, A-M., Webb, A., Johnson, J.E. and Payri, C.E. 2011. Vulnerability of mangroves, seagrasses and intertidal flats in the tropical Pacific to climate change. In: Bell J.D., Johnson, J.E. and Hobday, A.J. 2011. Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Chapter 4. pp. 311–368. Secretariat of the Pacific Community, Noumea, New Caledonia. 941 pages.

The natural absence of mangroves in the eastern Pacific is likely to be related to propagule dispersion rather than a lack of suitable conditions. The area inhabited by mangroves, relative to total land area, is also exceptional in some PICs. It is as high as 12% for FSM, about 10% for Palau and around 1–2% for another six PICs (Table 3).[40] Although the area covered by mangroves in PNG is only ~ 1% of total land area, the > 4,500 km^2 of mangroves represent > 70% of the mangrove area in the region (Table 3).[41]

Mangrove species form ecological assemblages, based on similarities in their morphology, physiology and reproduction strategies. They occur in highly humid to extremely arid environments, and on soil types that include clay, peat, sand and coral rubble.[42] Mangrove communities can differ markedly from each other due to the variation in tides, wave exposure, river flows and soils associated with different locations.[43,44,45] Mangrove trees create extensive and productive forests where conditions are optimal, but occur as dwarf and scattered shrubs where they are not.

Mangrove communities on high islands usually differ from those found on atolls because of variation in the availability of fresh water, sediments and nutrients from runoff.[46] As a result of local conditions and the potential for arrival of mangrove propagules,[47] each PIC has a unique combination of mangrove species. Only two species – *Bruguiera gymnorhiza* and *Rhizophora stylosa* – occur widely throughout the region as a result of their broad environmental tolerances.[48]

---

[40] Ellison, J.C. 2009. Wetlands of the Pacific Island region. *Wetlands Ecology and Management* 17, 169–206.
[41] Ellison, J.C. 2009. Wetlands of the Pacific Island region. *Wetlands Ecology and Management* 17, 169–206.
[42] English, S., Wilkinson, C. and Baker, V. 1997. Survey Manual for Tropical Marine Resources. 2nd edition, Australian Institute of Marine Science, Townsville, Australia.
[43] McLeod, E. and Salm, R.V. 2006. Managing mangroves for resilience to climate change. International Union for Conservation of Nature, Gland, Switzerland.
[44] Duke, N.C. 1992. Mangrove floristics and biogeography. In: Robertson, A.I. and Alongi, D.M. (Eds.) Tropical Mangrove Ecosystems, Coastal and Estuarine Studies, Volume 41. American Geophysical Union, Washington, United States of America, pp. 63–100.
[45] Alongi, D.M. 2009. The energetics of mangrove forests. Springer, Dordrecht, The Netherlands.
[46] Ellison, J.C. 2009. Geomorphology and sedimentology of mangrove swamps. In: Wolanski, E., Cahoon, D. and Gerardo Perillo, M.E. (Eds.) Coastal wetlands: An ecosystem integrated approach. Elsevier Science, Amsterdam, The Netherlands, pp. 564–591.
[47] De Lange, W.P. and De Lange, P.J. 1994. An appraisal of factors controlling the latitudinal distribution of mangrove (Avicennia marina var. resinifera) in New Zealand. *Journal of Coastal Research* 10, 539–548.
[48] Ellison, J.C. 2009. Geomorphology and sedimentology of mangrove swamps. In: Wolanski, E., Cahoon, D. and Gerardo Perillo, M.E. (Eds.) Coastal wetlands: An ecosystem integrated approach. Elsevier Science, Amsterdam, The Netherlands, pp. 564–591.

Table 3. Area (km^2) of coral reef, mangrove forest and seagrass meadow for each of the 14 GCF participating countries.

Pacific Island country	Coral reef[1]	Seagrass meadow[2]	Mangrove forest[3]
Melanesia			
Fiji	25,666	59.2	488.1
Papua New Guinea	27,086	117.2	4,524.7
Solomon Islands	8,535	79.0	526.5
Vanuatu	1,244	(27.0)*	15.8
Micronesia			
Federated States of Micronesia	15,074	48.7	87.9
Kiribati	4,320	2.8	1.5
Marshall Islands	13,930	0	0.3
Nauru	7	0	0
Palau	2,496	80.0	56.9
Polynesia			
Cook Islands	667	0	<0.1
Niue	56	0	0
Samoa	466	(14.3)*	2.3
Tonga	5,811	17.6	10.4
Tuvalu	3,175	0	<0.1

1 See ref[49], noting that the coral reef area for Fiji and PNG has been revised upwards based on analyses by S. Andrefouet (pers. comm.). 2 See ref[50].; 3 See ref[51]. *High confidence estimate not provided by McKenzie et al. (2021), estimate from the Allen Atlas (https://allencoralatlas.org/) used instead.

Mangrove assemblages have been classified into seaward, mid and landward zones, according to where they occur in relation to tidal position.[52] The seaward zone is the outfacing edge of the mangrove forest, which is fully exposed to all tides and frequent inundation. The soils in this zone are normally soft mud and sedimentary in origin. Mangrove species inhabiting the seaward zone usually have aerial roots that anchor and support the plant. The mid zone is subject to less regular tidal influences, with the trees generally being exposed to inundation only during the spring high tides. Soils are also sedimentary but more compacted than those in the seaward zone.

The landward zone is generally only inundated during the highest of spring tides, often receiving fresh water from groundwater or land runoff. It is dominated by mangrove 'associates', i.e. plants such as shrubs, ferns, vines, herbs and epiphytes generally found at the back of mangrove communities. The landward zone is usually a narrow strip of vegetation that may transition to a terrestrial forest.[53]

[49] Hoegh-Guldberg, O., Andréfouët, S., Fabricius, K.E., Diaz-Pulido, G., Lough, J.M., Marshall, P.A., Morgan, S. and Pratchett, M.S. 2011. Vulnerability of coral reefs in the tropical Pacific to climate change. In: Bell J.D., Johnson, J.E. and Hobday, A.J. 2011. Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Pages 251–296. Secretariat of the Pacific Community, Noumea, New Caledonia. 941 pages.

[50] McKenzie, L. J., Yoshida, R.L., Ainid, J.W., Andrefouet, S., Colin, P.L. *et al.* 2021. Seagrass ecosystems of the Pacific Island countries and territories: A global bright spot. *Marine Pollution Bulletin* 167. 112308 https://doi.org/10.1016/j.marpolbul.2021.112308.

[51] GMW http://www.globalmangrovewatch.org

[52] Claridge, D.A.B. and Burnett, J. 1993. Mangroves in focus. Wet Paper. Ashmore, Queensland, Australia.

[53] Claridge, D.A.B. and Burnett, J. 1993. Mangroves in focus. Wet Paper. Ashmore, Queensland, Australia.

Diversification of mangrove species can occur within these three broad habitat zones, for example, due to salinity gradients.[54]

Seagrasses

The Pacific Islands region has extensive seagrass meadows of over 24,000 km^2 in area (World Conservation Monitoring Centre data), with at least 14 species and one sub-species reported (Table 2).[55] However, seagrass may be more widespread as there are limited field surveys in some PICT and suitable environments for seagrass colonisation and growth exist (e.g. Cook Islands, Northern Mariana Islands). The greatest area and species diversity is in Melanesia, with Papua New Guinea (PNG) having the highest diversity (13 species), which decreases eastward across the region to two species in French Polynesia.[56] Seagrass meadows are under increasing threats from anthropogenic activities, especially land use change, further exacerbated by pressures from climate change.[57,58] However, in a global context, current evidence suggests the Pacific Islands region remains a location with relatively low pressures and more resilient seagrass.[59]

Mapping of seagrass habitats has been conducted by field surveys in some PICs (e.g. Solomon Islands) or by remote sensing in others, e.g. Palau.[60] Unfortunately, some seagrass surveys in the region have not measured the area of habitat (e.g. Vanuatu).[61] The surveys that have been done show that the area of shallow coastal waters where seagrasses occur is extensive in several PICs, e.g. in much of Micronesia, where the area they cover is equal to 16% of land area in Palau, and 5–6% in FSM (Table 3). Seagrasses are absent or unreported from Cook Islands, Nauru, Niue and Tuvalu. However, the lack of reported seagrass in Cook Islands may be the consequence of limited surveys of all locations suitable for establishment of these plants.[62]

Most seagrasses in the tropical Pacific Ocean are found in waters shallower than 10 m. However, there is great variation in seagrass habitats across the region, depending on water clarity, nutrient

[54] Robertson, A.I., Danial, P.A. and Dixon, P. 1991. Mangrove forest structure and productivity in the Fly River, Papua New Guinea. *Marine Biology* 111, 147–155.

[55] McKenzie L.J., Yoshida R.L., Aini J.W., Andréfouet S., Colin P.L., Cullen-Unsworth L.C., Hughes A.T., Payri C.E., Rota M., Shaw C. and Skelton P.A. 2021. Seagrass ecosystems of the Pacific Island Countries and Territories: A global bright spot. *Marine Pollution Bulletin*, 167, 112308.

[56] McKenzie L.J., Yoshida R.L., Aini J.W., Andréfouet S., Colin P.L., Cullen-Unsworth L.C., Hughes A.T., Payri C.E., Rota M., Shaw C. and Skelton P.A. 2021. Seagrass ecosystems of the Pacific Island Countries and Territories: A global bright spot. *Marine Pollution Bulletin*, 167, 112308.

[57] Cullen-Unsworth L., Unsworth, R. 2013. Seagrass meadows, ecosystem services, and sustainability. *Environment: Science and policy for sustainable development*, 55(3), 14-28.

[58] Grech A., Chartrand-Miller K., Erftemeijer P., Fonseca M., McKenzie L., Rasheed M., Taylor H., Coles R. 2012. A comparison of threats, vulnerabilities and management approaches in global seagrass bioregions. *Environmental Research Letters*, 7(2), 024006.

[59] McKenzie L.J., Yoshida R.L., Aini J.W., Andréfouet S., Colin P.L., Cullen-Unsworth L.C., Hughes A.T., Payri C.E., Rota M., Shaw C. and Skelton P.A. 2021. Seagrass ecosystems of the Pacific Island Countries and Territories: A global bright spot. *Marine Pollution Bulletin*, 167, 112308.

[60] Hily, C., Duchêne, J., Bouchon, C., Bouchon-Navaro, Y. and others. 2010. Les Herbiers de Phanérogames Marines de l'Outre-Mer Français. Initiative Française pour les Récifs Coralliens, Conservatoire du littoral, France.

[61] Chambers, M.R., Nguyen, F. and Navin, K.F. 1990. Seagrass communities. In: Done, T.J. and Navin, K.F. (Eds.) Vanuatu Marine Resources. Report of a Biological Survey. Australian Institute of Marine Science, Townsville, Australia, pp. 92–103.

[62] Hoegh-Guldberg, O., Andréfouët, S., Fabricius, K.E., Diaz-Pulido, G., Lough, J.M. Marshall, P.A. and Pratchett, M.S. Vulnerability of coral reefs in the tropical Pacific to climate change. In: Bell J.D., Johnson, J.E. and Hobday, A.J. 2011. Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Chapter 4. pp. 251–296. Secretariat of the Pacific Community, Noumea, New Caledonia. 941 pages.

availability and exposure to wave action. Based on the influence of these factors, five main categories of seagrass habitat have been recognized (Figure 1).[63,64,65] Descriptions of these five categories are provided below.

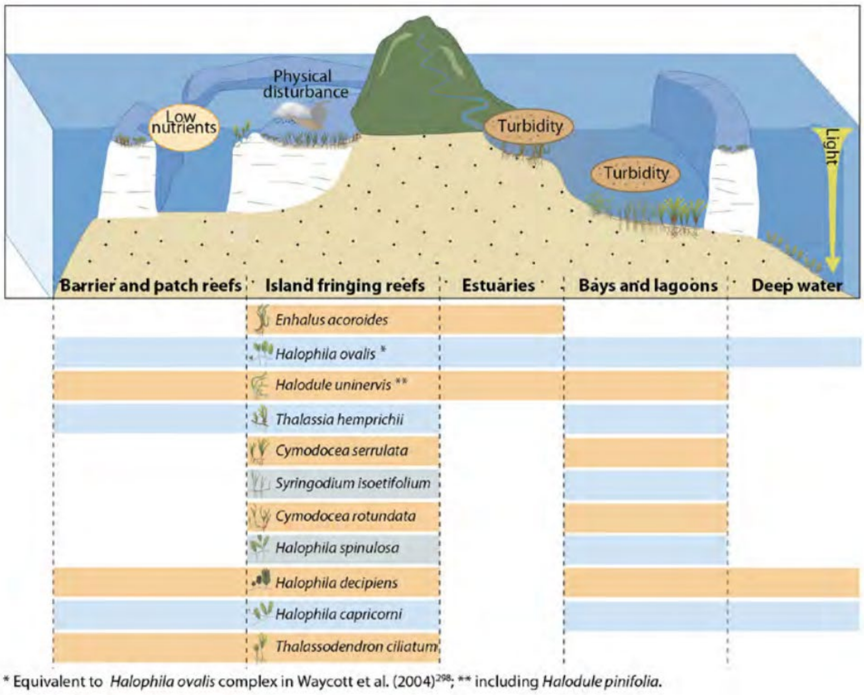

Figure 1. The five main habitats where seagrasses occur in the tropical Pacific Ocean, together with the factors limiting growth of seagrasses in each habitat.[66]

---

[63] McKenzie, L.J. and Rasheed, M.J. 2006. Seagrasses: Pohnpei Island and atoll marine assessment: Technical report of survey conducted 26 October–3 November 2005. Seagrass-Watch HQ, Department of Primary Industries and Fisheries, Cairns, Australia.

[64] McKenzie, L., Campbell, S.J. and Lasi, F. 2006. Seagrasses and mangroves. In: Green, A., Lokani,P., Atu, W., Ramohia, P., Thomas, P. and Almany, J. (Eds.) Solomon Islands marine assessment: Technical report of survey conducted 13 May–17 June 2004. The Nature Conservancy, Pacific Islands Country Report 1/06, Brisbane, Australia, pp. 401–443.

[65] Chambers, M.R., Nguyen, F. and Navin, K.F. 1990. Seagrass communities. In: Done, T.J. and Navin, K.F. (Eds.) Vanuatu marine resources. Report of a biological survey. Australian Institute of Marine Science, Townsville, Australia, pp. 92–103.

[66] Hoegh-Guldberg, O., Andréfouët, S., Fabricius, K.E., Diaz-Pulido, G., Lough, J.M. Marshall, P.A. and Pratchett, M.S. Vulnerability of coral reefs in the tropical Pacific to climate change. In: Bell J.D., Johnson, J.E. and Hobday, A.J. 2011. Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Chapter 4. pp. 251–296. Secretariat of the Pacific Community, Noumea, New Caledonia. 941 pages.

IPCC projections for tropical coastal fish habitats

An IPCC Special Report[67] was published in 2018 on the impacts of global warming of 1.5°C above pre-industrial levels and related global GHG emission pathways in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. The report projected that global warming of 1.5°C will shift the ranges of many marine species to higher latitudes, as well as increase the amount of damage to many ecosystems. It was also expected to drive the loss of coastal resources and reduce the productivity of fisheries and aquaculture (especially at low latitudes). The risks of climate-induced effects are projected to be higher at 2°C than those at global warming of 1.5°C (with high confidence). Coral reefs are projected to decline by a further 70–90% at 1.5°C (with high confidence) with larger losses (> 99%) at 2°C (with very high confidence) by 2100. The report forecast that the risk of irreversible loss of many marine and coastal ecosystems increases with global warming, especially at 2°C or more (high confidence).

A subsequent IPCC Special Report[68] in 2019 advised that warm-water coral reefs and rocky shores dominated by immobile, calcifying (e.g. shell- and skeleton-producing) organisms, such as corals, barnacles and mussels, were observed to be affected by extreme temperatures and ocean acidification (with high confidence). Marine heatwaves had resulted in large-scale coral bleaching events at increasing frequency (with very high confidence), causing worldwide reef degradation since 1997, with slow recovery (more than 15 years) if it occurs (with high confidence).

In relation to projected risks to ecosystems, the 2019 IPCC report advised that, under enhanced stratification of the water column, reduced nutrient supply is projected to cause tropical ocean NPP to decline by 7–16% (very likely range) under RCP8.5 by 2081–2100 (with medium confidence). In tropical regions, marine animal biomass and production are projected to decrease more than the global average under all emissions scenarios in the 21st century (with high confidence). Almost all warm-water coral reefs are projected to suffer significant losses of area and local extinctions, even if global warming is limited to 1.5°C (with high confidence). The species composition and diversity of remaining reef communities is projected to differ from present-day reefs (with very high confidence). The 2019 report advised that future shifts in fish distribution and decreases in their abundance and fisheries catch potential due to climate change are projected to affect income, livelihoods and food security of marine resource-dependent communities (medium confidence). The 2019 report also noted that the long-term loss and degradation of marine ecosystems compromises the ocean's role in cultural, recreational and intrinsic values important for human identity and well-being (medium confidence).

The decline in warm-water coral reefs is projected to greatly compromise the services they provide to society, such as food provision (with high confidence), coastal protection (with high confidence) and tourism (with medium confidence). Increases in the risks for seafood security (with medium confidence) associated with decreases in seafood availability are projected to elevate the risk to nutritional health in some communities highly dependent on seafood (with medium confidence), such

---

[67] Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J.B.R., Chen, Y., Zhou, X., Gomis, M.I., Lonnoy, E., Maycock, T., Tignor, M. and Waterfield, T. (Eds.). 2018. Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. IPCC. 632 pages.

[68] Pörtner, H.-O., Roberts, D.C., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E., Mintenbeck, K., Alegría, A., Nicolai, M., Okem, A., Petzold, J., Rama, B. and Weyer, N.M. (Eds.). 2019. IPCC Special report on the ocean and cryosphere in a changing climate. IPCC. 765 pages.

as those from small island developing states. Such impacts compound any risks from other shifts in diets and food systems caused by social and economic changes and climate change over land (with medium confidence).