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Chapter 6

Vulnerability of mangroves, seagrasses and intertidal flats in the tropical Pacific to climate change

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> *'One of the major challenges in the Pacific Islands region is adjusting to the responses of coastal ecosystems to climate change.'* (Gilman et al. 2006)[i]

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[i] Gilman et al. (2006) *Pacific Island Mangroves in a Changing Climate and Rising Sea*. United Nations Environment Programme Regional Seas Reports and Studies 179, Nairobi, Kenya.

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6.1 Introduction

In addition to the extensive coral reef habitats described in Chapter 5, the shallow subtidal and intertidal zones around the coasts of Pacific Island countries and territories (PICTs) often support large areas of mangroves and seagrasses. Intertidal sand and mud flats[ii] with their associated microalgae and infauna are also common features of most PICTs.

Due to their varying responses to light, temperature and hydrology, and the capacity of mangroves and seagrasses for dispersal[1–4], these three ecosystems usually form a mosaic. Typically, mangroves are located along the shore, whereas seagrasses and intertidal flats can extend long distances away from the shoreline in lagoons and sheltered bays, and often adjoin coral reefs. In many places, coral reefs buffer waves coming ashore to create suitably sheltered environments for the establishment of mangroves and seagrasses[5].

Mangroves and seagrasses are of special interest to coastal fisheries worldwide because of the role they play in providing nursery areas for commonly harvested fish and invertebrates[6–9]. Although the ecology of fish and invertebrates associated with mangroves and seagrasses in the tropical Pacific is not well understood compared with other parts of the world, the connectivity among mangroves, seagrasses, intertidal flats and coral reefs indicates that mangroves and seagrasses throughout the region provide a similar function to such habitats elsewhere.

In addition to their roles as nursery areas, mangroves, seagrasses and intertidal flats provide feeding habitats for many species of adult demersal fish, some of which reside on reefs during the day and forage over seagrasses and intertidal flats at night[10]. Seagrasses and intertidal flats are also permanent habitats for several species of sea cucumbers, the main group of invertebrates targeted as an export commodity in the region[11], and for a wide range of molluscs gleaned for subsistence. Overall, the range of coastal fisheries resources that depend on mangroves, seagrasses and intertidal flats is extensive, with many of these species important to the food security and livelihoods of coastal communities in PICTs (Chapters 1 and 9).

The separate values of each ecosystem are surpassed by the productivity that results when they are inter-connected[7,8,12]. In particular, movement of nutrients, detritus, prey and consumers between habitats can have major effects on the structure and productivity of food webs, with nutrient and detrital subsidies increasing primary and secondary productivity both directly and indirectly[13]. In addition to supporting fisheries, mangroves provide protection against wind and wave energy, and stabilise shorelines; and both mangroves and seagrasses improve water quality by trapping sediments, nutrients and other pollutants[14–18].

[ii] Includes intertidal areas of sand and mud above mean low tide level, but does not include intertidal coral reefs or seagrasses.

Ecosystems dominated by mangroves and seagrasses are being eroded in some PICTs due to their proximity to developments in the coastal zone[19,20]. For example, increases in the turbidity of coastal waters and higher rates of sedimentation, resulting from poor land management in the catchments of high islands, are reducing the area and health of seagrass habitats[21,22]. The problem is not unique to the region – the range and intensity of anthropogenic effects on coastal habitats have been increasing worldwide, reducing the extent and quality of mangroves[23,24] and seagrasses[20,25].

Climate change is expected to exacerbate anthropogenic impacts on mangroves, seagrasses and intertidal flats[3,26,27]. Further losses are expected to occur as a result of greater heat stress, increased sedimentation and turbidity due to higher rates of runoff, changes in suitable sites for growth of mangroves and seagrasses due to rising sea levels, and possibly more physical damage from the combination of sea-level rise and more severe cyclones and storms.

In this chapter, we assess the vulnerability of the mangrove, seagrass and intertidal flat habitats in the tropical Pacific that support coastal fisheries. We do this by examining the effects that changes to surface climate and the tropical Pacific Ocean (Chapters 2 and 3) are expected to have on the plants that define these habitats. This exposure to change is used in the framework described in Chapter 1 to assess the vulnerability of the habitats under representative low (B1) and high (A2) emissions scenarios from the Intergovernmental Panel on Climate Change (IPCC) for 2035 and 2100[28].

We commence by describing the diversity and distribution of mangrove, seagrass and intertidal flat habitats in the tropical Pacific (25°N–25°S and 130°E–130°W), outlining the role they play in supporting coastal fisheries in the region, and summarising the critical requirements for establishing and maintaining these habitats. Next, we summarise the limited information on the observed effects of climate change on mangroves, seagrasses and intertidal flats, and assess the expected vulnerability of these habitats to the projected changes in solar radiation, air and sea temperatures, rainfall, nutrients, cyclones and storms, ocean acidity and sea-level rise. For mangroves and seagrasses, we integrate these assessments to estimate changes in area under the various scenarios.

We conclude by identifying the uncertainty associated with these assessments, the important gaps in knowledge, the research required to fill these gaps, and the key management measures needed to maintain the important roles that the mangroves, seagrasses and intertidal flats of the region play in supporting coastal fisheries.

6.2 The nature of mangroves, seagrasses and intertidal flats in the tropical Pacific

6.2.1 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 tolerances. This variability in tolerance to saline conditions contributes to patterns of species distribution across the intertidal zone.

The tropical Pacific has an extraordinary diversity of mangroves – 31 of the 70 species recognised globally are found in the region, including five hybrids. Twenty-three species occur in Papua New Guinea (PNG), making it the country with the greatest diversity of mangroves in the world[29]. The diversity of mangroves decreases progressively from west to east across the region, with only four species and one hybrid occurring in Samoa (**Table 6.1**). In French Polynesia, the single species of *Rhizophora* is likely to have been introduced[30,31] and has proliferated on all the high islands of the Society archipelago[31]. 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 PICTs. It is as high as 12% for the Federated States of Micronesia (FSM), about 10% for Palau and around 1–2% for another six PICTs[29] (**Table 6.1**). Although the area covered by mangroves in PNG is only ~ 1% of total land area, the 4640 km^2 of mangroves represent > 70% of the mangrove area in the region[29].

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[32]. Mangrove communities do differ markedly from each other, however, due to the variation in tides, wave exposure, river flows and soils associated with different locations[5,33,34]. 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 also usually differ from those found on atolls, because of variation in the availability of fresh water, sediments and nutrients from runoff[35].

As a result of local conditions and the potential for arrival of mangrove propagules[36], each PICT has a unique combination of mangrove species. Nevertheless, two species – *Bruguiera gymnorhiza* and *Rhizophora stylosa* – occur in 15 of the 22 PICTs as a result of their broad environmental tolerances[35].

Table 6.1 Number of mangrove and seagrass species recorded from Pacific Island countries and territories (PICTs), together with the estimated area of mangrove and seagrass habitats.

PICT	Total land area (km^2)	Mangrove			Seagrass			References
		Species (hybrid)	Area (km^2)	% land	Species	Area (km^2)	% land	
Melanesia								
Fiji	18,272	7(1)	424.6	2.32	6	16.5[a]	0.01	29, 54, 260–263
New Caledonia	19,100	15(3)	205	1.07	11	936	5.0	22, 29, 52, 260, 263–267
PNG	462,243	31(2)	4640	1.00	13	117.2	0.03	29, 268–272
Solomon Islands	27,556	17(2)	525	1.90	10	66.3	0.24	21, 22, 29
Vanuatu	11,880	14(3)	25.2	0.21	11	?[a]		29, 40, 44, 261, 273, 274
Micronesia								
FSM	700	15(1)	85.6	12.23	10	44	6.29	21, 29, 260, 263, 274–277
Guam	541	12	0.7	0.13	4	31	5.73	260, 261, 263, 277–280
Kiribati	690	4	2.6	0.37	2**	?[b]		29, 44, 260, 281
Marshall Islands	112	5	0.03	0.27	3	?[b]		29, 44, 260, 274
Nauru	21	2	0.01	0.05	0	0	0	29, 282
CNMI	478	3	0.07	0.01	4	6.7	1.40	29, 44, 260, 274, 283, 284
Palau	494	14(1)	47.1	9.53	11	80	16.19	29, 260, 285–289
Polynesia								
American Samoa	197	3	0.5	0.26	4	?[c]		29, 44, 274, 279, 290
Cook Islands	240	0	0	0	0	0	0	29, 291, 292
French Polynesia	3521	1	?[b]	?	2	28.7	0.82	29, 265, 293, 294
Niue	259	1	0	0	0	0	0	29
Pitcairn Islands	5	0	0	0	0	0	0	295
Samoa	2935	3	7.5	0.26	5	?[b]		29, 44, 54, 279
Tokelau	10	0***	0	0	0	0	0	29, 296
Tonga	699	7	13	1.87	4	?[b]		29, 260, 263, 290
Tuvalu	26	2	0.4	1.54	1*	0	0	29
Wallis and Futuna	255	2	0.2	0	5	24.3	17.0	29, 46, 47, 297

* Local contacts report no seagrass but Ellison (2009)[29] noted the presence of one species; ** based on observations by P Anderson; *** includes one associate species; a = mapping currently in progress; b = not mapped; c = seagrass not encountered during September 2002 and May 2003 surveys of Tutuila, Manua Group, Rose Atoll and Swains Island (source: Analytical Laboratories of Hawaii 2004)[284].

Mangrove assemblages have been classified into seaward, mid and landward zones, according to where they occur in relation to tidal position[37] (**Figure 6.1**). 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 only to inundation during the spring high tides. Soils are also sedimentary but more compacted than those in the seaward zone. They usually contain carbon and sometimes have inorganic fine grain-sizes. 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, vines, herbs and epiphytes generally found at the back of mangrove communities. Indeed, the landward zone is usually a narrow strip of vegetation that may transition to a terrestrial forest[37]. Diversification of mangrove species can occur within these three broad habitat zones, for example, due to salinity gradients[38].

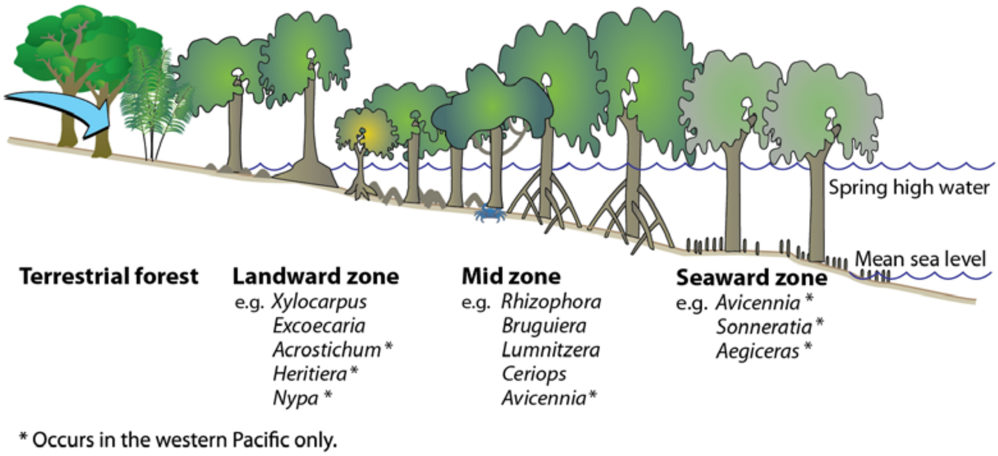


Figure 6.1 The three zones typical of mangrove habitats in the tropical Pacific, showing the differences in mangrove species typical of each zone.

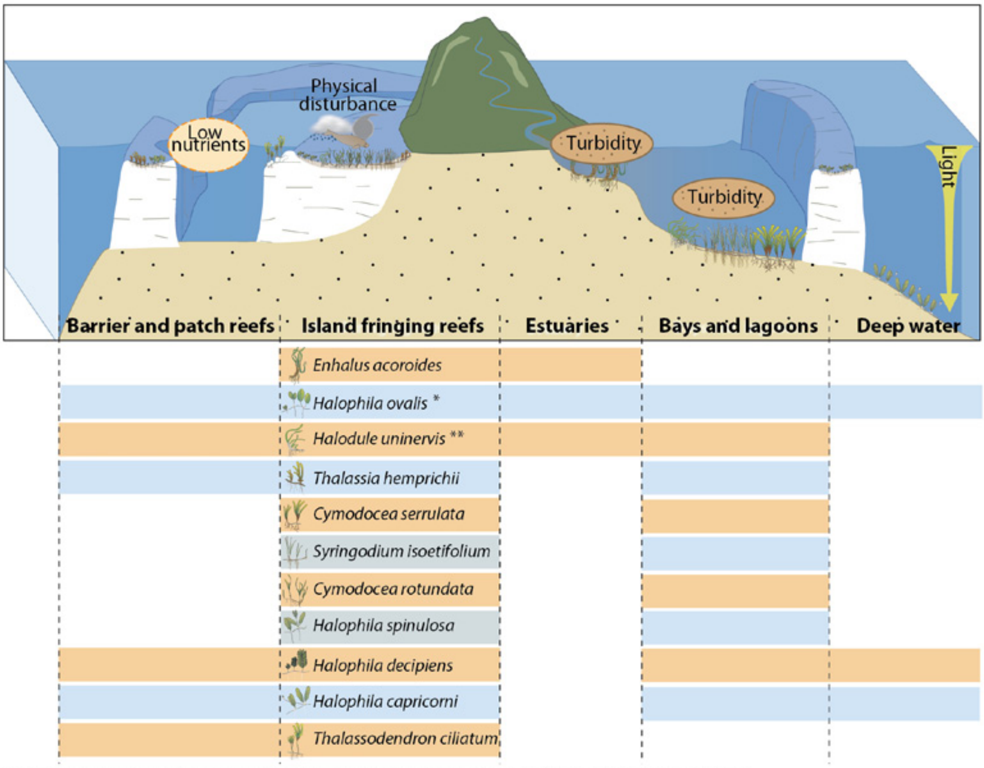
6.2.2 Seagrasses

Fourteen species and one subspecies of seagrass have been reported from the tropical Pacific (**Table 6.1**). Like mangroves, the greatest number of seagrasses occurs in PNG and diversity declines to the east (**Table 6.1**). Seagrasses are absent or unreported from the Cook Islands, Nauru, Niue, Pitcairn Islands, Tokelau and Tuvalu. However, the discontinuity of seagrass in the Cook Islands and Tokelau may be the consequence of limited surveys because both of these PICTs have deep, sheltered lagoons and low-energy environments suitable for establishment of these plants.

The area of shallow coastal waters where seagrasses occur is extensive in several PICTs. For example, seagrasses are an important habitat in much of Micronesia, where they are equal to 16% of land area in Palau, and 5–6% in FSM and Guam (**Table 6.1**). Seagrasses are also important habitats in Wallis and Futuna, and New Caledonia, where they cover areas equivalent to 17% and 5% of land area, respectively (**Table 6.1**). The area of seagrass is particularly significant in New Caledonia, where it covers > 900 km^2. Mapping of seagrass habitats has been conducted by field surveys in some PICTs (e.g. Solomon Islands) or by remote sensing in others, e.g. New Caledonia, Wallis and Futuna, Palau, Guam and Commonwealth of the Northern

Mariana Islands (CNMI)[39]. Unfortunately, some seagrass surveys in the region have not measured the area of habitat (e.g. Vanuatu)[40]. Mapping of seagrass is currently underway in Fiji.

Most seagrasses in the tropical Pacific are found in waters shallower than 10 m. However, there is great variation in the nature of seagrass habitats across the region, depending on water clarity, nutrient availability and exposure to wave action[21,22,40]. Based on the influence of these factors, five main categories of seagrass habitat have been recognised[21,22,40] (**Figure 6.2**). These categories are described below.



	Barrier and patch reefs	Island fringing reefs	Estuaries	Bays and lagoons	Deep water
Enhalus acoroides		✓	✓		
Halophila ovalis *	✓	✓	✓	✓	✓
Halodule uninervis **	✓	✓	✓	✓	
Thalassia hemprichii	✓	✓		✓	
Cymodocea serrulata		✓		✓	
Syringodium isoetifolium		✓		✓	
Cymodocea rotundata		✓		✓	
Halophila spinulosa		✓		✓	
Halophila decipiens	✓	✓		✓	✓
Halophila capricorni	✓	✓		✓	✓
Thalassodendron ciliatum	✓	✓			

* Equivalent to *Halophila ovalis* complex in Waycott et al. (2004)[298]; ** including *Halodule pinifolia*.

Figure 6.2 The five main habitats where seagrasses occur in the tropical Pacific, together with the factors limiting growth of seagrasses in each habitat.

6.2.2.1 Bays and lagoons

Calm clear waters and a range of stable sandy substrates in bays, and in lagoons behind reefs or in atolls, enable a diverse range of seagrass species to establish dense meadows in both subtidal and intertidal areas. *Halodule uninervis* often grows well in such locations, from the intertidal zone to depths of 30 m. In some places, it is patchy and intermixed with other seagrass species (e.g. *Halophila* spp.). Another dominant species in these locations is *Syringodium isoetifolium,* which often occurs in shallow, subtidal areas (1–6 m deep) of lagoons behind barrier reefs. *Syringodium* is more tolerant of oxidised substrata than other species and is usually the first species to re-establish after a disturbance[41]. In French Polynesia, *Halophila ovalis* is a common species on the shallow sandy substrata of Tuamotu atolls, where this seagrass usually mixes with macroalgae, forming dense mats.

6.2.2.2 Island fringing reefs

Wide fringing reefs, found where wave action is slight to moderate, provide subtidal and intertidal areas with stable sediments that support diverse and dense seagrass meadows. Even so, the seagrasses inhabiting fringing reefs may differ widely because of variation in exposure to solar irradiation, nutrient availability, wave action and the associated movement of sediments[3,42]. Where runoff from high islands delivers nutrients, seagrasses on the landward edge of fringing reefs can be highly productive. Pooling of water at low tide on the landward side of fringing reefs allows the seagrasses there to attain greater leaf heights, and prevents desiccation of the plants. In contrast, intertidal areas expose seagrasses to damage, particularly when low tides occur during the day in summer.

Variation in environmental conditions across fringing reefs often results in a succession of seagrass communities. In particular, seagrasses in the genera *Thalassia* and *Cymodocea* often dominate inshore intertidal areas because they tolerate a moderate level of disturbance[43]; *Halophila ovalis*, *Halodule* spp. and *Syringodium isoetifolium* occur in shallow water on fringing reef platforms[44] and *Thalassodendron ciliatum,* which has strong woody rhizomes and roots, attaches to rock and coral rubble banks at depths of 6–8 m on the seaward margin of fringing reefs[45]. In Wallis and Futuna, the seagrass meadows on the fringing reef nearest the beach are dominated by *Halodule* spp., whereas *Halophila ovalis* is most common in the middle of the reef and *S. isoetifolium* on the seaward edge[46,47].

6.2.2.3 Barrier and patch reefs

Physical disturbance from waves and the movement of sediment usually prevent seagrasses from growing on the windward sides of barrier reefs. However, they occur on the leeward side of islands, or where the back-reef is large[21,22,40]. *Thalassia hemprichii* is common on barrier reefs because it is able to tolerate shallow sediments, high temperatures and strong currents. In Solomon Islands, *Enhalus acoroides*, which has robust rhizomes and roots, is common on barrier reefs with strong currents in Malaita. In contrast, seagrasses are not a common feature on the barrier reef in New Caledonia.

In some very rare situations, *Halodule uninervis* can form scattered patches mixed with *Halophila ovalis.* Conversely, *Cymodocea* spp., *Halodule uninervis* and *T. hemprichii* form dense beds on lagoonal patch reefs[48]. Some species of seagrass (e.g. *Halophila decipiens, Cymodocea rotundata* and *T. hemprichii*) also grow on shallow subtidal patch reefs[21]. These environments have suitable conditions for growth because there is limited disturbance from wave action, protection from currents by the reef crest, and availability of coarse carbonate sediments.

6.2.2.4 Estuaries

Seagrasses grow in the lower reaches of estuaries on the high islands of Melanesia. However, growth is limited in these extreme environments by fluctuations in light and salinity, and scouring by currents[49]. Seagrass meadows in estuaries are generally dominated by structurally large species, such as *Enhalus acoroides*, which are tolerant of high temperatures and low salinity[50], and can withstand partial burial[51]. Seagrasses in estuaries have more microalgal and macroalgal epiphytes than seagrasses in other habitats[21].

6.2.2.5 Deep water

Little is known about the few species of seagrass that occur in deeper water in the tropical Pacific. *Halophila decipiens* is commonly reported from depths of 60 m in New Caledonia[52], interesting given that this species commonly occupies coral reef habitats also. This species also occurs in French Polynesia, where it grows on the sandy bottom of channels and embayments, and the outer reef slope[53]. It has also been reported from depths of ~ 40 m in Solomon Islands[22], and 10 to 25 m at the Great Sea Reef, Fiji[54]. In New Caledonia, a closely related species, *Halophila capricorni,* is also commonly observed on the sandy bottom of channels near coral reefs at depths of 20 to 30 m[52].

6.2.3 Intertidal flats

In many PICTs, a proportion of the coastal zone between the active sandy beach margin and mean low tide comprises sandy or muddy intertidal flats. These habitats are also often associated with the margins of lagoons on atolls and high islands. Mangroves frequently border the landward margin of intertidal flats, whereas seagrasses and/or coral reef often occur at the seaward edge. The transition from intertidal sand or mud flats to mangroves or seagrasses is dictated by comparative vertical elevation in relation to mean sea level.

There is limited understanding of the role of intertidal flats, and the associated food webs, in supporting the fish and invertebrates that contribute to subsistence and small-scale commercial coastal fisheries in PICTs (Chapter 9). However, intertidal locations and shallow marine ecosystems (< 1 m deep) in other parts of the world yield some of the highest rates of primary production through growth of the benthic microalgae (BMA) community[55] and, globally, the area of intertidal flats is about three times greater than that of mangrove forests[56]. Although the areas of intertidal flats have yet to be mapped for the vast majority of the main islands in the region, it is clear that they can comprise significant areas, and support important fisheries (Box 6.1).

Box 6.1 Importance of intertidal flats

The extent, and ecological and socio-economic roles of intertidal flats in the tropical Pacific are still poorly understood. However, elsewhere these habitats (1) play a significant role in nutrient cycling and primary production in shallow coastal ecosystems; (2) support high densities and large harvests of burrowing (infaunal) invertebrates, e.g. arc shells *Anadara* spp.; and (3) help mediate pollution (eutrophication) through denitrification by enhanced bacterial processes within the surface layers of sediment and burrows of infauna.

In the 16 equatorial atolls of the Gilbert's Group, Kiribati, and in several other Pacific Island countries and territories (PICTs), the contribution of intertidal flats to the subsistence of coastal communities is frequently overlooked. These habitats can be highly productive, and communities often glean molluscs, polychaetes, crustaceans and echinoderms from these areas at low tide for household food supplies. People also earn income from harvesting edible species from intertidal flats and selling them fresh or preserved to urban markets, or as export commodities in the case of sea cucumbers.

Greater attention must be given to estimating the areas of intertidal flats in PICTs, their ecological function, and their contributions to food security and livelihoods, especially as these habitats are highly vulnerable to being lost as a result of projected sea-level rise. The significance of intertidal flats to coastal fisheries in some PICTs is illustrated by Tarawa Atoll in Kiribati, where (1) the land area of ~ 31 km^2 at high tide, increases to 52 km^2 during low spring tides, expanding the total 'land' area by ~ 170%; and (2) total annual harvests of arc shells have been estimated to be as high as 1800 tonnes per year (Chapter 9).

Women gleaning from an intertidal flat in Kiribati

Photo: Arthur Webb

Although intertidal flats lack conspicuous vegetation, and are often considered to be 'unvegetated' or 'bare', they frequently support a rich diversity and abundance of BMA communities, comprising photosynthetic microalgae (diatoms, dinoflagellates and cyanobacteria) and reducing and oxidising bacteria[57,58]. The high rates of benthic primary productivity by these BMA communities in turn support a rich array of benthic epifauna (animals living on the sediment surface), and infauna (burrowing organisms). Transient fish species feed on this fauna during high tide, and birds frequent these habitats at low tide to prey on the wide range of food found there.

6.3 The role of mangroves, seagrasses and intertidal flats in supporting fisheries in the tropical Pacific

The mosaic of mangrove, seagrass and intertidal flat habitats plays an important role in supporting the demersal fish and invertebrates that contribute to the subsistence and commercial coastal fisheries of the region[59,60] (Chapter 9). For example, several important demersal fish species associated with coral reefs use this habitat mosaic as a nursery area[59,61,62], and for feeding when they are adults[63]. There is also the possibility that juvenile fish may use mangrove and seagrass habitats in sequence as they develop, before residing permanently on coral reefs. As adults, several species of demersal fish venture from reefs into adjacent mangrove or seagrass areas to forage at night, depending on which habitat is nearby. Mangroves, seagrasses and intertidal flats are also the primary habitats of important invertebrate species, such as sea cucumbers, crabs and molluscs[64,65] (Chapter 9).

Below, we describe the specific roles played by mangroves, seagrasses and intertidal flats as habitats for the fish and invertebrates that underpin coastal fisheries in the tropical Pacific, and as fishing areas.

6.3.1 Mangroves

A large number of fish and invertebrate species harvested in the tropical Pacific by subsistence and commercial coastal fisheries are associated with mangroves during their life cycle (**Tables 6.2** and **6.3**). These species contribute to three of the four categories of coastal fisheries described in Chapter 9: demersal fish, invertebrates targeted for export commodities, and invertebrates gleaned from intertidal and shallow subtidal habitats for subsistence (**Figure 6.3**). In PNG, mangroves are also the location of recreational fisheries for barramundi and black bass[66].

Harvesting of fish and invertebrates from mangrove habitats is divided into activities that capture (1) resident species, like arc shells *Anadara* spp., oysters *Crassostrea* spp., mangrove crabs *Scylla* spp. and sea cucumbers *Holothuria scabra*[65–70], or (2) species of fish and shrimp that use mangroves temporarily during high tide, e.g. banana prawns *Fenneropenaeus merguiensis*[71].

Mangroves also contribute to coastal fisheries in two other ways. First, they provide important nursery (feeding and shelter) areas for juvenile fish and invertebrates[27,72–77]. Second, they are intermittent feeding areas for adult fish normally harvested from coral reefs or other habitats[70,78]. The nursery value of mangroves stems from the refuge their dense roots provide[79], the food resources found there[63], and reduced flow rates[80]. The larger species of fish that feed within inundated mangrove habitats include carnivores, such as snappers (Lutjanidae), trevallies (Carangidae) and barramundi *Lates calcarifer*, which feed on the juvenile fish sheltering there[78]; and herbivores-detritivores, such as mullet (Mugilidae)[27], herring (Clupeidae)[81] and shrimp[27,82].

Table 6.2 The number of species associated with mangrove and seagrass habitats, as juveniles and/or adults, for families of fish caught by coastal fisheries in Pacific Island countries and territories (PICTs). All information is preliminary due to the lack of extensive sampling of fish in mangrove and seagrass habitats in many PICTs.

Family*	Common name	Habitat		
		Mangrove	Seagrass	Both
Acanthuridae	Surgeonfish	3	3	3
Atherinidae	Hardy head	5	3	3
Belonidae	Long tom	3	3	3
Bothidae	Flounders	2	2	2
Carangidae	Trevallies	4	2	2
Clupeidae	Herring	7	8	7
Dasyatidae	Rays	5	5	5
Engraulidae	Anchovies	4	4	4
Gerreidae	Silver biddies	5	5	5
Haemulidae	Grunts	5	5	5
Hemiramphidae	Halfbeaks	5	4	4
Labridae	Wrasses	3	3	3
Leiognathidae	Ponyfish	7	4	4
Lethrinidae	Emperors	5	5	5
Lutjanidae	Snappers	7	4	4
Polynemidae	Threadfins	3	3	3
Mugillidae	Mullet	9	6	6
Mullidae	Red mullet	7	5	5
Nemipteridae	Threadfin bream	2	2	2
Platycephalidae	Flatheads	4	2	2
Scaridae	Parrotfish	2	2	2
Serranidae	Groupers	8	3	3
Siganidae	Rabbitfish	4	4	4
Sillaginidae	Whiting	4	4	4
Sphyraenidae	Barracuda	3	3	3
Synodontidae	Lizardfish	3	2	2
Teraponidae	Grunters	3	3	3

* Families of fish mostly with only one species harvested from either mangrove or seagrass habitats include Chandidae (milkfish), Chirocentridae (wolf herring), Cynoglossidae (tongue sole), Drepanidae (sicklefish), Elopidae (giant herring), Lacteriidae (snapper), Megalopidae (tarpon), Monacanthidae (leatherjacket), Scatophagidae (butterfish), Scombridae (Spanish mackerel), Soleidae (sole), Sparidae (bream) and Toxotidae (archer fish).

The value of any given area of mangroves for fisheries is linked, however, to the availability of adjacent habitats. Because many parts of the mangrove habitat drain completely at low tide, fish and shrimp can use these areas only when they are inundated, and must rely on nearby subtidal habitats for shelter at other stages of the tidal cycle[83]. The most commonly used subtidal adjacent habitats are drainage channels within and beside mangroves, which often contain fallen timber from mangrove trees (snags) and areas of seagrass[84]. Thus, mangrove-based food webs are linked to the attributes of nearby areas (**Figure 6.4**), and any assessment of the value of mangroves to fisheries species needs to consider the availability of adjacent habitats.

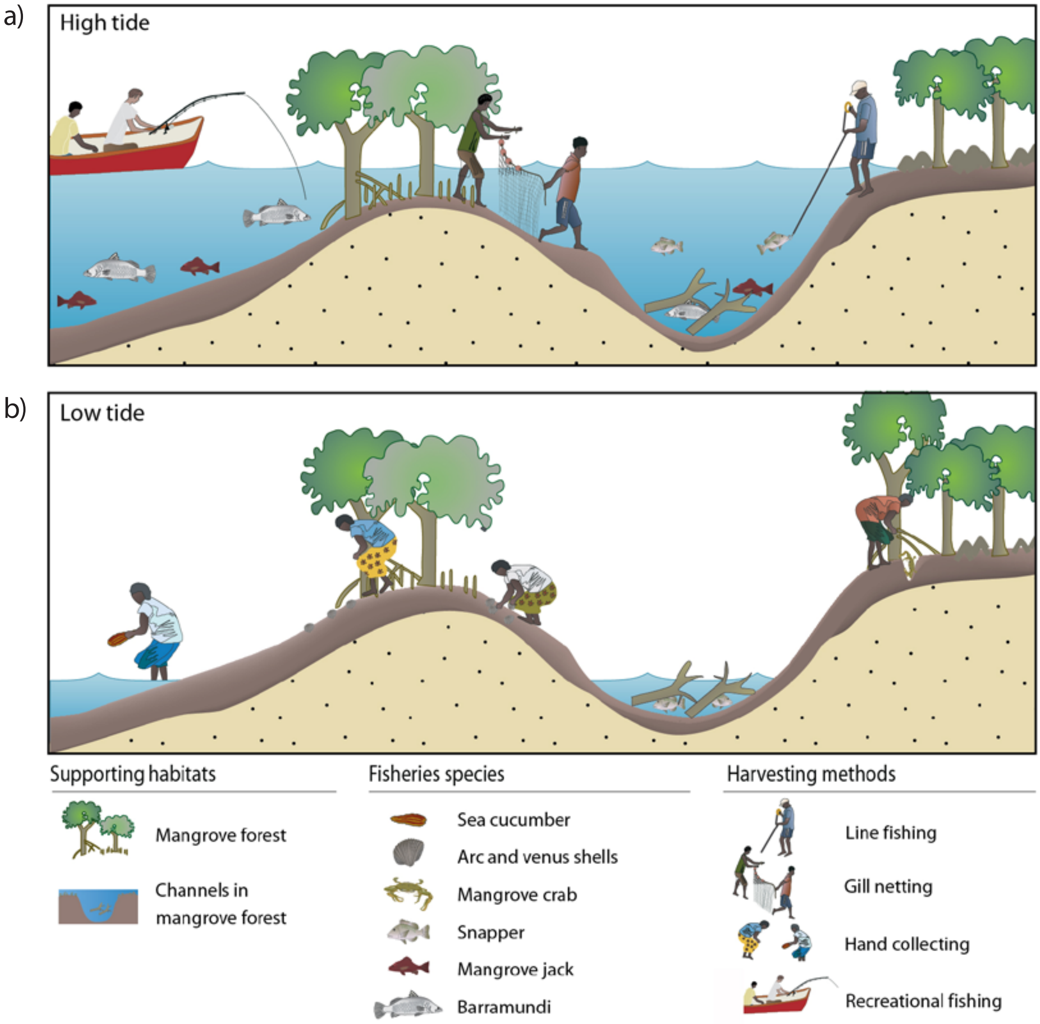


Figure 6.3 The subsistence and commercial coastal fishing activities that occur in mangrove habitats in the tropical Pacific at (a) high tide, and (b) low tide.

Table 6.3 The number of species associated with mangrove and seagrass habitats, as juveniles and/or adults, for the main groups of invertebrates caught by coastal fisheries in Pacific Island countries and territories (PICTs). All information is preliminary due to the lack of extensive sampling of invertebrates in mangrove and seagrass habitats in many PICTs. Blank spaces indicate that the invertebrate group does not commonly occur in the habitat.

Invertebrate group	Common name	Habitat		
		Mangrove	Seagrass	Both
Holothuridae	Sea cucumber		3	
Portunidae	Crab	5	3	3
Penaeidae	Shrimp	6		3
Palinuridae	Spiny lobster		1	
Thalassinoidea	Mud lobster	1		
Paguroidea	Hermit crab	2	3	
Stomatopoda	Mantis shrimp	1	2	
Cephalopda	Octopus		3	
Echinoidea	Sea urchin		3	
Bivalvia	Arc shell*	4	4	2
Gastropoda	Whelk*	3	2	1
Sipunculida	Peanut worm	2	2	2

* Indicates that several species are included under this broad common name.

6.3.2 Seagrasses

Seagrasses are also a vital part of the mosaic of habitats that support many of the demersal fish and invertebrates harvested by coastal fisheries (Chapter 9) (**Figure 6.5**). Seagrasses are thought to play a particularly important role in the coastal fisheries of New Caledonia, Palau, FSM, Guam and Wallis and Futuna, where relatively large areas of this habitat occur (**Table 6.1**), and in the large lagoons of Solomon Islands where rabbitfish (*Siganus* spp.) support subsistence and commercial fisheries[85,86].

Although the physical structure of seagrasses is not as robust as mangrove roots, the leaves of many seagrasses (e.g. *Thalassia* spp., *Thalassodendron* spp., *Cymodocea* spp., and *Syringodium isoetifolium*) are relatively tall and at high leaf densities can provide juvenile fish and invertebrates with much protection from predation[87]. Many seagrass meadows also remain submerged at low tide, which means that juvenile fish, shrimp and crabs can shelter there throughout the tidal cycle, feeding on zooplankton delivered by currents, and the epiphytes and epifauna on seagrass leaves. The seagrass leaves themselves also provide food for large numbers of species[88]. For these reasons, seagrass beds provide nursery areas for a wide range of fish and invertebrates that live on coral reefs or in other habitats as adults[89–91]. Tropical species of seagrass vary greatly in their structural complexity and therefore do not all provide the same degree of shelter. Nevertheless, even seagrasses with comparatively low leaf heights and densities can support high numbers of juvenile fish and invertebrates[87].

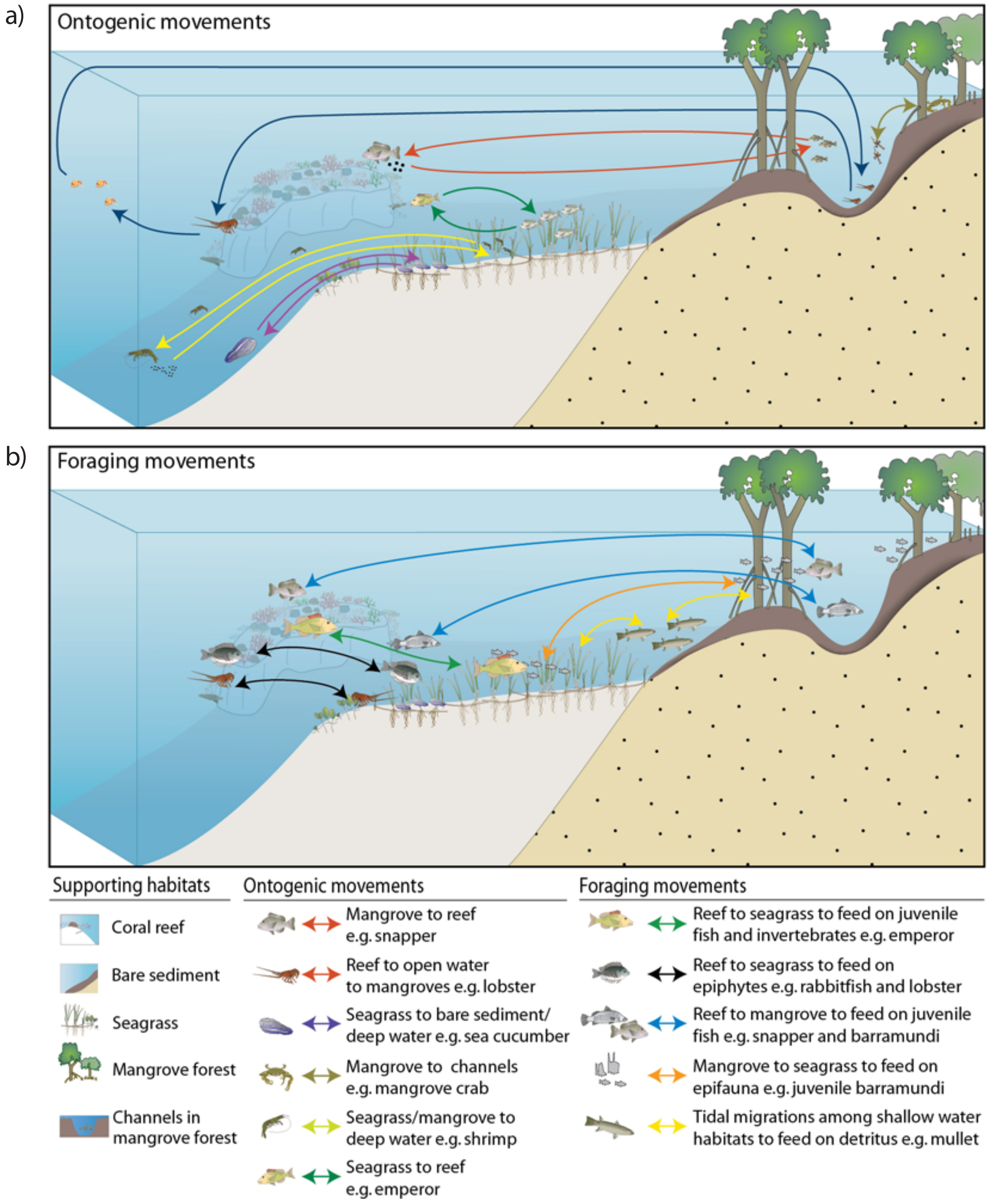


Figure 6.4 The mosaic of mangroves, seagrasses and coral reefs that occur in the coastal waters of many Pacific Island countries and territories, showing (a) the ontogenic movements of fish and invertebrate species among habitats as they grow; and (b) the foraging movements of adult fish and invertebrates from reefs to mangroves and seagrasses at night to feed. Note that diagrams depict high tide.

Many fish also visit seagrass meadows as adults to forage for food. The juvenile fish and invertebrates associated with seagrass attract a range of predatory fish from nearby coral reefs at night to feed. These species include emperors (Lethrinidae)[21] and snappers[92]. Herbivorous and omnivorous fish and invertebrates, such as the barred halfbeak *Hemiramphus far*, scribbled rabbitfish *Siganus spinus* and goatfish *Barberinus* sp. have been observed within seagrass beds in Solomon Islands[85]. Spiny lobsters (Palurinidae) also feed frequently on seagrass epiphytes and seagrass leaves[93].

In addition to the fish and invertebrate species that use seagrass meadows as nurseries or intermittent feeding areas, a wide range of valuable invertebrates live permanently in seagrass habitats, especially sea cucumbers[11,65,85], sea urchins, other bivalves and octopus[85,93–95]. These species are harvested during low tide[96,97], and are often gleaned by women and children for household food (Chapter 9).

6.3.3 Intertidal flats

The species of fish and invertebrates caught over intertidal flats and the methods used to catch them differ depending on geographic location, the tide and the season. The capture of demersal fish using gill nets, seine nets and hand lines occurs during high tide, whereas the gleaning of a range of molluscs, crustaceans, sea cucumbers and polychaetes occurs at low tide[98–100] (**Figure 6.6**). Furthermore, the harvest of some species (e.g. mantis shrimp) relies on first identifying and marking burrows at low tide, and then returning on the incoming tide to capture the shrimp as it emerges to hunt. The responses of fish and invertebrates to phases of the moon and seasons are understood by coastal communities and used to harvest some species over monthly or annual cycles[70,74].

The diversity and abundance of fish of species occurring on intertidal flats at high tide depends on the proximity of mangroves, seagrasses and/or coral reefs, and estuaries. This is not the case for infaunal invertebrates, which have limited mobility. For burrowing molluscs, crustaceans and polychaete worms, the intertidal sediments provide shelter from predation by birds, and desiccation at low tide. However, some species emerge at low tide, e.g. fiddler crabs, which feed on the BMA community that thrives in these shallow, sunlit habitats[101]. Carnivorous fish, such as bonefish *Albula* spp., rays (Dasyatidae) and trevallies (Carangidae) use the flats during high tide to prey on infauna. Herbivorous/detritivorous mullet and milkfish *Chanos chanos* also visit intertidal flats at high tide to feed directly on the BMA community[63,72]. Our preliminary understanding of intertidal flats in the tropical Pacific, like similar habitats in other parts of the world, indicates that their assemblages of BMA and infauna directly and indirectly support a wide variety of species[102].

The diverse range of fishing and gleaning activities that occur on intertidal flats make important contributions to food security and livelihoods in many PICTs. For example, in Kiribati, harvests of arc shells from intertidal flats at low tide have exceeded 3000 tonnes per year in the western Gilberts Group (Chapter 9). These bivalves comprise a regular and preferred part of the daily diet and can be a particularly important food for people in urban areas who cannot regularly catch or purchase fresh fish or other foods.

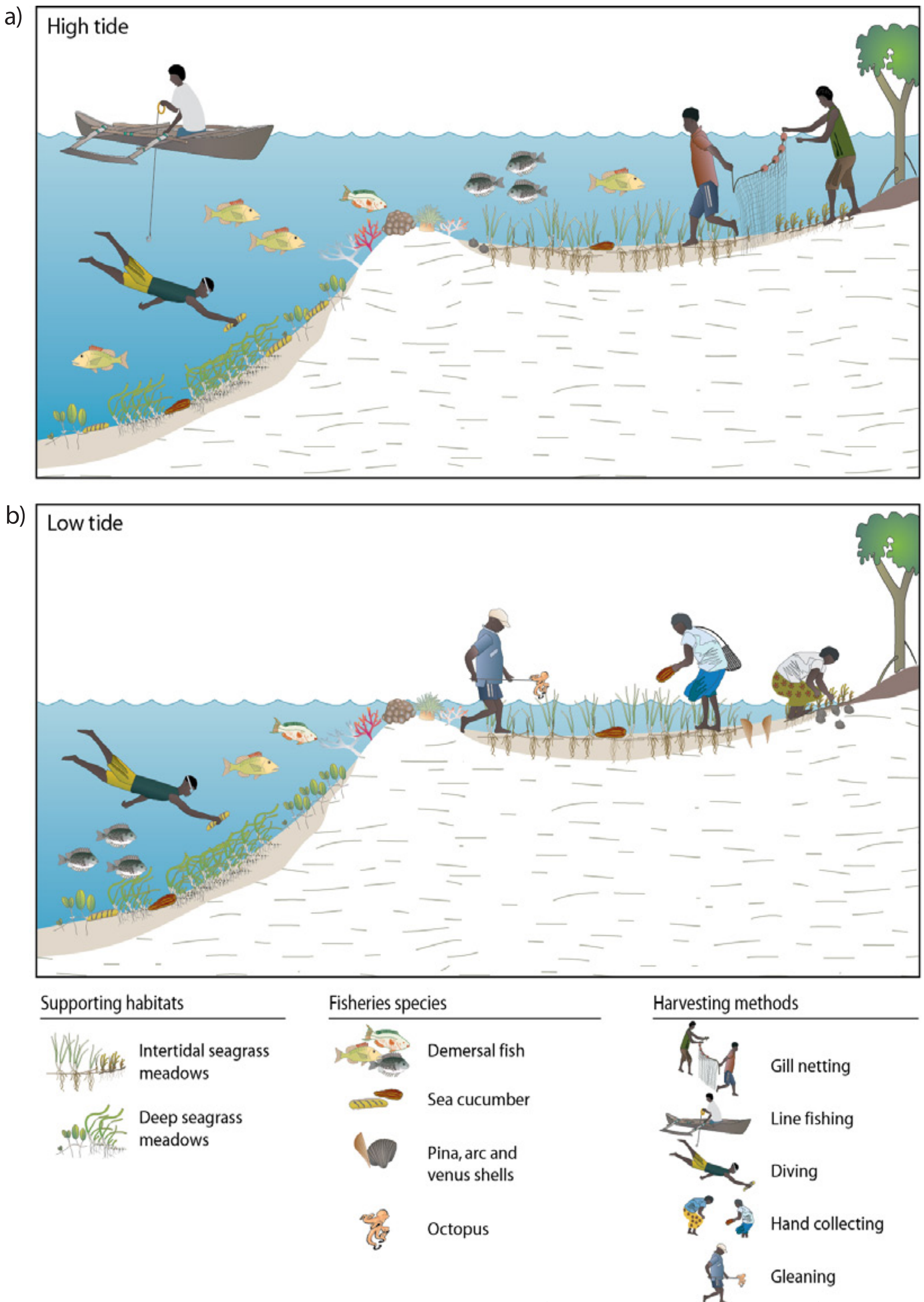


Figure 6.5 Subsistence and commercial coastal fishing activities in seagrass habitats in the tropical Pacific at (a) high tide, and (b) low tide.

Polychaete worms are also harvested and dried in rural areas of Kiribati and shipped to urban South Tarawa. These harvests provide an important source of income for people in rural areas. Recreational fisheries for bonefish (*Albula* spp.) in Cook Islands, Kiribati and New Caledonia also centre on productive intertidal sand flats.

6.4 Critical requirements for maintaining mangroves, seagrasses and intertidal flats

6.4.1 Solar radiation

Like all plants, mangroves and seagrasses need light for photosynthesis. However, light is rarely limiting for mangroves within the tropical and subtropical habitats where they occur – their light requirements for maximal photosynthesis are considerably less than the amount of light available on cloudless days. On the other hand, excessive irradiance can raise leaf temperatures and predispose mangroves to photoinhibition[103,104]. Elevated levels of ultraviolet radiation in the tropics can also inhibit growth of mangroves by disrupting protein synthesis and depressing photosynthesis via stomatal closure.

Mangroves have adapted to their environment by developing 'sun' and 'shade' leaves. Shade leaves are larger and thinner than sun leaves, with a higher volume-to-surface ratio and fewer stomata[103,105]. Also, leaves developing in high light intensity have more adaptations to guard against desiccation than those developing in low light intensity[103,106]. In general, there are two broad groups of mangroves (1) species which are somewhat shade-tolerant both as seedlings and adults (e.g. *Rhizophora stylosa* and *Bruguiera parviflora*), and (2) those that are shade intolerant (e.g. *B. gymnorhiza* and *Laguncularia racemosa*).

In contrast, light often limits the distribution, species composition, biomass and growth rates of seagrasses[107–110]. These flowering plants have high minimum light requirements compared with other marine primary producers[111] because they (1) have a high respiratory demand to support a large non-photosynthetic biomass of roots and rhizomes, (2) can only use a restricted spectral range of light, and (3) must regularly oxygenate their root zone to compensate for anoxic sediments. The high minimum light requirement restricts seagrasses to shallow coastal areas where sunlight can penetrate. There are, however, differences in light requirements among species. For example, *Halophila* spp. generally have a low minimum light requirement and can grow at greater depths than other species[112].

The BMA communities which inhabit the upper few centimetres of intertidal flats typically have high turnover rates and are composed of a diverse range of heterotrophic and autotrophic species which include photosynthetic algae[57,58].

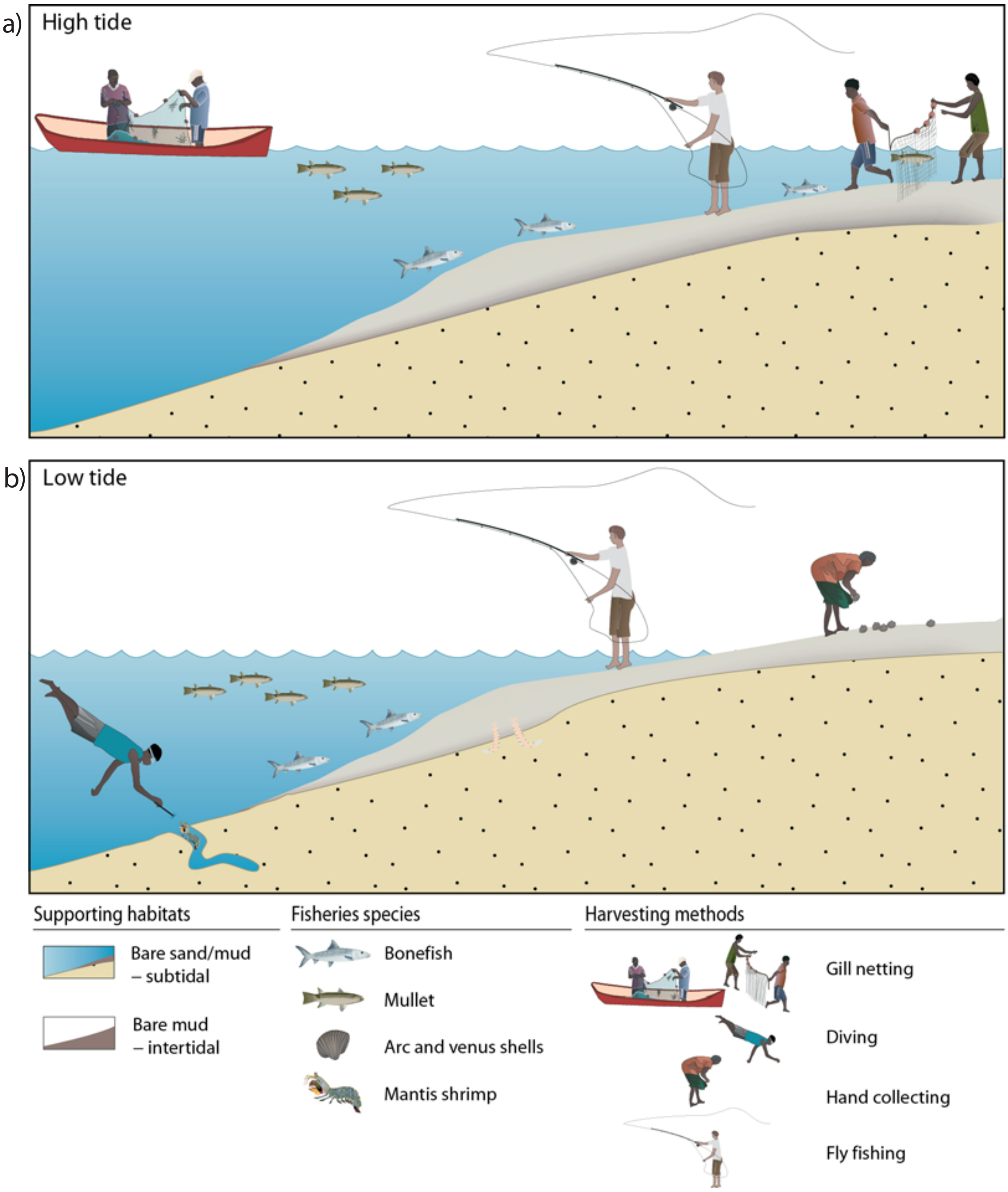


Figure 6.6 The subsistence and commercial coastal fishing activities that occur over intertidal sand and mud flats in the tropical Pacific at (a) high tide, and (b) low tide.

The greater proportion of the BMA population is usually confined to the upper 10 mm or so of the sediment surface[113–115] and primary productivity within the BMA community, derived from autotrophic species, such as cyanobacteria and diatoms, is the main source of *in situ* organic matter production in this habitat. Intertidal BMA species may also migrate vertically within the upper few centimetres of sediment.

This may be a response to avoid excessive heat, light, desiccation and/or predation[114]. Benthic microalgal assemblages can also adapt physiologically to ambient light conditions by varying the amount of chlorophyll they contain; this photo-adaptation response can occur in, for example, turbid estuary conditions[116]. Given the exposed nature of intertidal BMA communities at low tide, and shallow water depths during high tide, light is not generally considered to be a significant limiting factor to BMA productivity in the intertidal zone.

6.4.2 Temperature

Temperature is a critical factor for the survival and growth of plants because the enzymes involved in most cellular processes operate most efficiently within specific temperature ranges. Mangroves need warm temperatures for photosynthesis, respiration and energy processes involving salt regulation and extrusion, water uptake and growth. As a result, the northern and southern limits of most mangrove species coincide with the 20°C winter isotherm[117]. The heat tolerance of mangroves is less well studied, although the optimum temperature for photosynthesis of mangroves is < 35°C, and little or no photosynthesis occurs at 40°C[118,119]. Also, the rates of assimilation and water evaporation from plant pores are more efficient at leaf temperatures of 25–35°C, and decline sharply with increases above 35°C[120,121].

Tropical seagrasses require water temperatures of 25–35°C, otherwise the energy created from photosynthesis may not exceed the energy used for respiration[122]. Where water temperature rises to 35–40°C, photosynthesis declines due to the breakdown of photosynthetic enzymes[123] and the carbon balance of the plants goes into deficit because respiration continues to increase. Under such circumstances, growth rates of some tropical seagrasses can decrease because they have a limited capacity to store carbohydrates. These temperature thresholds vary among species[122] and seasons[124]. Thus, tropical seagrasses usually occur only in intertidal habitats where maximum summer temperatures are < 40°C[122,123]. They can survive higher temperatures for short periods, but prolonged exposure leads to the ‘burning’ of leaves or plant mortality.

The BMA communities of intertidal flats often live in extreme physiochemical conditions, especially during periods when low tide corresponds to midday sun exposure (high temperatures and UV exposure) or heavy rainfall (large changes in ambient salinity). Studies of temperature-related control over BMA community composition and productivity are limited mainly to temperate climates[125–127], where temperature appears also to be linked to changes in light[128]. Increases in temperature within the optimum range in these temperate environments marginally increase microalgal photosynthetic rates and nutrient uptake[129]. However, the effects of higher average temperatures on BMA communities within the environments of the tropical Pacific are unknown.

6.4.3 Nutrients and salinity

Growth and production of mangroves also depends on adequate supplies of macronutrients and micronutrients. Key plant macronutrients are: nitrogen, phosphorus, sulphur, magnesium, calcium and potassium. Micronutrients required for plant growth include: iron, manganese, copper, zinc, nickel, boron chloride, sodium, silicon, cobalt, selenium and aluminium. Sulphur, magnesium, potassium, boron, chloride and sodium are rarely limiting because they occur naturally in sea water. The critical need for nitrogen and phosphorus by mangroves has been demonstrated repeatedly through nutrient addition experiments[130,131], with most studies reporting limitation of one or both nutrients. However, the importance of nitrogen and phosphorus varies with location and position in the mangrove forest[131,132].

Mangroves have adaptations that allow them to tolerate high levels of salinity – membranes in cells at the root surface exclude most of the salt. The salt that does enter the plant is either excreted via the leaves or stored in leaves until they die and are shed, depending on the mangrove species. Because of the limited availability of fresh water in the soils of the intertidal zone, mangrove plants have also developed ways of limiting the amount of water they lose through their leaves. They can restrict the opening of their stomata, and have the ability to vary the orientation of their leaves to reduce evaporation during the harsh midday sun[133].

The most important macronutrients for seagrasses are carbon, nitrogen and phosphorus. Seagrasses do not grow at their full capacity unless these macronutrients are available in sufficient quantities[134,135]. The carbonate sediments found in reef environments typically bind phosphorus, reducing its availability for seagrasses, whereas sediments derived from the land are limited in nitrogen[136]. This general pattern can vary, however, depending on local nutrient inputs and sediment properties[137]. The levels of nutrients in some sediments in the tropical Pacific, e.g. those at Dravuni in Fiji, are among the lowest recorded for seagrass ecosystems[138].

Where nutrients are added to seagrass meadows that are normally nutrient-limited, the plants generally show an increase in growth and biomass[139,140]. However, excessive nutrients can lead to proliferation of phytoplankton, macroalgae or algal epiphytes on seagrass leaves and stems, reducing the amount of light reaching the seagrass[141,142]. Eutrophication of shallow estuaries and lagoons can also lead to the proliferation of bloom-forming ‘ephemeral’ macroalgae, which can shade and eventually displace seagrasses[143]. The impacts of nutrients on seagrasses in the tropical Pacific are usually localised to small bays, areas near human settlements[21,22], or areas adjacent to activities such as shrimp aquaculture, which have damaged some mangroves or seagrasses in New Caledonia[144]. Seagrasses generally grow best at salinities of 35 practical salinity units (PSU), although seagrasses have been observed growing in salinities of 4 to 65 PSU, with some species being more tolerant of extremely low salinity[145].

Benthic microalgae communities at the sediment surface obtain nutrients from the water column and interstitial water below the illuminated upper sediment layer[146]. However, due to tight coupling between mineralising bacteria and BMA production within the upper sediment layers, nutrients from the water column can play a relatively unimportant role[147]. The BMA community also intercepts and assimilates nutrients which may otherwise be fluxed from sediments to the overlying water column and may limit pelagic primary productivity in this way[58,148]. Indeed, significant concentrations of ammonium (NH_4^+), nitrate (NO_3^-), silicate (SiO_2) and phosphate (PO_4^{3-}) may be intercepted and prevented from entering the overlaying water column by BMA communities[149–151].

Benthic microalgae communities have relatively ready access to nutrients in sediments, which results in an inconsistent response to addition of nutrients to the water column. Nutrient loading has been shown to either increase BMA biomass and productivity[125,152] or have little effect[150,153]. Also, 'blooms' of BMA that occur in response to nutrient loading, seasonal change and removal of BMA grazers[154,155] are controlled by the two-dimensional nature of the BMA habitat. The ready supply of organic matter associated with productive BMA communities, and the mineralisation of this material by bacteria, are also associated with important processes such as denitrification[150,151,156]. Just as cyanobacteria are associated with nitrogen fixation[57], denitrifying bacteria in the lower anoxic layer of sediments can contribute to the substratum being a net sink for dissolved inorganic nitrogen and its removal via denitrification as nitrogen gas[151,157]. Net rates of denitrification are enhanced by the presence of burrowing infauna[157,158]. Thus, it is likely that the typically bioturbated intertidal flats of the tropical Pacific may play an important mediating role in nutrient processing and productivity.

Photo: Johann Bell

Women collecting arc shells ('palourde') in New Caledonia

In nutrient-limited systems typical of the more pristine coastal habitats of the tropical Pacific, the productivity of BMA is likely to be a more important contributor to primary production than phytoplankton (Chapter 4). In fact, BMA communities can be a major source of organic carbon input into shallow coastal ecosystems via the assimilation of sediment-born nutrients[57,113,156]. This in turn supports benthic epifauna and infauna populations, which contribute directly and indirectly to subsistence and commercial coastal fisheries and other biogeochemical processes that mediate or enhance the release of nutrients[157–159]. The vital role of BMA can change, however, in shallow areas subject to eutrophication, sustained high turbidity and/or intense physical disturbance. Under such conditions, BMA productivity may be greatly depressed and phytoplankton productivity in the upper water column can become more dominant[160].

6.4.4 Soils/sediments

Mangroves grow in various combinations of sand, silt and clay, which are often rich in organic matter (detritus). Sandy soils are porous and facilitate water percolation and aeration during low tide, while clays are less well aerated. Differences in soil types can have an effect on the distribution of mangrove genera, e.g. *Avicennia* and *Sonneratia* thrive in sandy areas, *Rhizophora* are found in peat soils and contribute to the formation of peat[161], and *Bruguiera* favour heavy clays containing little organic matter[162]. The subsoils in mangrove ecosystems are typically waterlogged, have little aeration and a heavy load of organic material decomposing at a slow rate. The oxygen content of only the first few millimetres of soil is replenished by the circulation of tidal water and exchange with the atmosphere. Below that, the organic load and fine particle size result in anoxic conditions. A supply of oxygen to the roots is vital for plant growth and nutrient uptake[134]. Consequently, mangroves in many locations rely on internal transport of gases to meet their oxygen requirements. The metabolic costs involved in this process reduce the rate of plant growth[163].

Sediment characteristics are also important in determining the growth, germination, survival and distribution of seagrasses[164–166]. In particular, sediment texture affects levels of nutrients and diffusion of oxygen[167]. Sandy sediments have lower fertility and diffuse oxygen more readily[167,168]. Conversely, finer-textured sediments usually have higher fertility and greater levels of anoxia because pore water has less interaction with the overlying water column[169]. The effects of anoxia on seagrass are complex – anaerobic conditions can stimulate germination in some species[170] but can also result in elevated sulphide levels, which inhibit production of leaf biomass in mature plants[171,172]. Sulphide is also toxic to seedlings of some species[173]. Overall, however, there is still insufficient information to identify the ‘ideal’ sediment types for seagrass[169].

Low-energy intertidal environments (i.e. lagoon sands and mud flats) generally yield the greatest BMA production[55]. Comparatively larger BMA communities are found in sandy sediment rather than fine silt and mud due to limited penetration of light into the finer sediments (e.g. light penetration into quartz sands may be more than twice as deep as into mud)[174]. Sandy sediments also tend to allow enhanced movement of interstitial water and therefore dissolved gases (e.g. oxygen and carbon dioxide) and nutrients. This provides a deeper habitat with favourable conditions for the BMA community[58].

Benthic microalgae communities can also influence the physical properties of sediments by enhancing the stability of the sediment surface via the secretion of mucous threads that bind sediment grains. In some cases, this results in formation of continuous mats over the sediment surface[58,114,175]. These mats greatly reduce resuspension of sediments due to wave action and water movement, and nutrient flux due to interstitial sediment flushing. This effectively regulates nutrient release into the water column from comparatively nutrient-rich deeper sediment zones[58,156,176].

6.5 Recent variation in mangroves, seagrasses and intertidal flats linked to climate change

6.5.1 Mangroves

Mangroves are sensitive to even minor transitions in coastal conditions, such as altered drainage patterns, saltwater intrusion, accretion or erosion in response to changes in sea level[35]. The response of mangroves to these changes can be seen through variations in the composition and relative abundance of plant species within the mangrove habitat[23,177,178]. Although the responses may be gradual, particularly in undisturbed systems, the alterations in coverage and composition of species can be used to assess the effects of climate change and other environmental impacts on mangrove habitats. This can be demonstrated through palaeo-environmental reconstruction[178], geographic information systems (GIS)[179], or ecosystem monitoring[180].

Examples of recently observed changes in mangrove ecosystems in the tropical Pacific associated with sea-level rise include (1) gradual retreat of mangrove zones in southern PNG in response to rates of sea-level rise similar to those projected globally[178,181] (**Figure 6.7**); and (2) GIS analysis of shoreline change over four decades in three mangrove areas in American Samoa, where there was landward movement of seaward margins of 25, 64, and 72 mm per year during sea-level rise of ~ 2 mm per year[179]. A study from the Caribbean also demonstrates the response of mangrove ecosystems to changes in sea level – the largest area of mangroves in Bermuda has been reduced by 26% due to retreat of the seaward edge, owing to inundation stress caused by sea-level rise of 2.8 mm per year[182,183]. In parts of Micronesia, mangrove sediment accretion rates are also not keeping pace with current rates of sea-level rise[184,185].

The success of flowering and ‘seed set’ of three species of mangroves in Fiji has been influenced by rainfall patterns[186,187]. Higher success was found on the west coast of Viti Levu relative to the dry coast, and in normal years relative to drought years.

In general, detection of changes in mangrove cover and health in the tropical Pacific has been limited and difficult because adequate baseline data and monitoring are usually lacking[29]. A shortage of meteorological, hydrological, hydro-geological and water quality data in many PICTs[188] compounds the problem. In addition, the limited data on the physical, chemical and biological processes in catchments, including soil erosion, loss of biodiversity and land clearing[189] (Chapter 7), make it difficult to separate the effects of coastal development and land use practices on mangrove habitats from any effects of climate change.

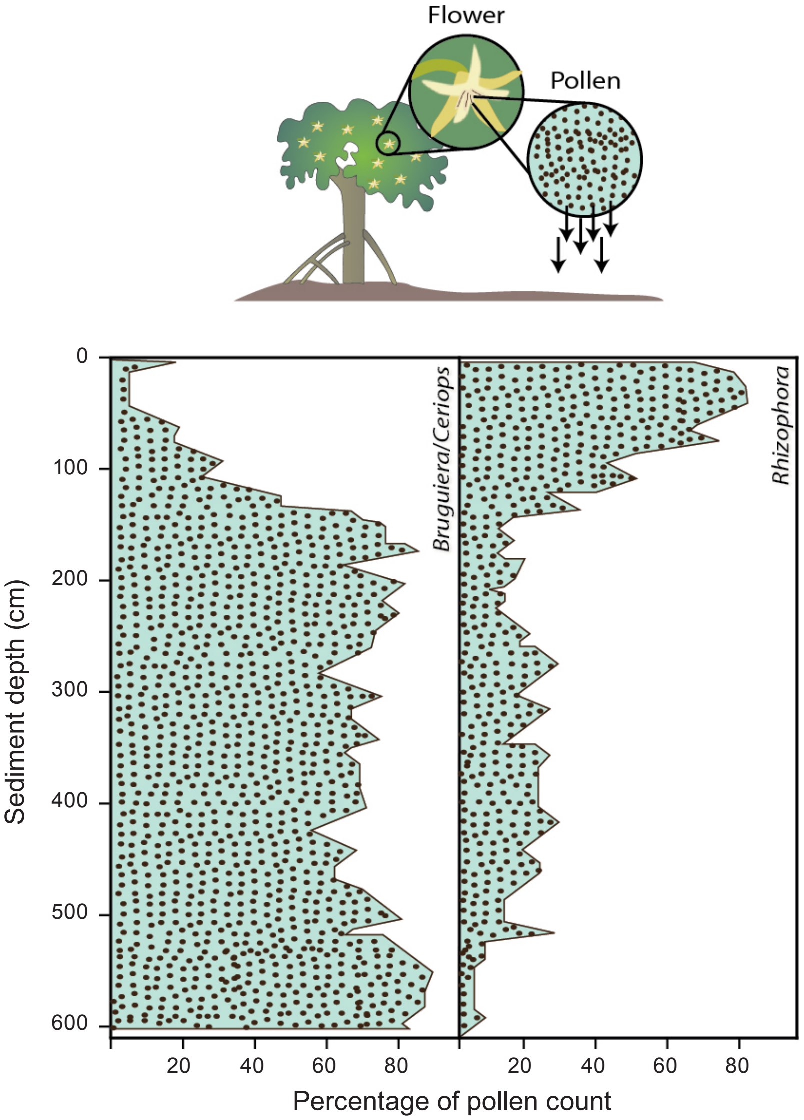


Figure 6.7 Replacement of the mangrove *Bruguiera* by *Rhizophora* within the past 3000 years in the Tipoeka Estuary, Papua New Guinea (based on sedimentary rock strata and pollen data), demonstrating gradual landward retreat of high island mangroves during sea-level rise rates of 0.7 mm per year (source: Ellison 2008)[181].

6.5.2 Seagrasses

Estimates of recent changes in seagrass habitats across the tropical Pacific are difficult to make because (1) seagrass meadows are known to fluctuate seasonally, and change from year to year[190,191]; and (2) maps of the distribution of seagrass area and biomass are either limited or imprecise. Isolated instances of seagrass burn-off (blackened dying leaves) have been observed on fringing reefs in Fiji. Although this burning is caused by exposure to elevated temperatures[122], there are insufficient data to conclude that these events are occurring at increasing rates. In other parts of the world, temperature-related seagrass losses have been recorded (e.g. southern Australia), and high temperatures have caused large-scale diebacks of *Amphibolis antarctica* and *Zostera muellerii*[192].

6.5.3 Intertidal flats

There has been little research on the impacts of climate change on intertidal flat habitats and their associated BMA communities and infauna in the tropical Pacific. The most likely impacts are from rising sea levels. However, the gradual rates of sea-level rise since the beginning of the industrial era, and the effects of atmospheric pressure and El Niño-Southern Oscillation (ENSO) on sea level (Chapter 3), make any effects difficult to detect, particularly against the background of high natural variability. The task is made all the more difficult because where intertidal flats are close to urban areas any effects of climate change would be confounded by direct human impacts, such as pollution, extraction of sand and coral for construction, coastal development, over-harvesting of infauna and changes in water quality.

6.6 Projected vulnerability of mangroves, seagrasses and intertidal flats to climate change

6.6.1 Mangroves

6.6.1.1 Solar radiation

Exposure and sensitivity

Mangrove habitats in much of the tropical Pacific are expected to be exposed to reductions in light as a result of the increase in the percentage of cloudy days due to intensification of the hydrological cycle (Chapter 2). Conversely, in New Caledonia, projected decreases in rainfall of 5–10% by 2035 and 5–20% by 2100, and in cloudy days, are expected to increase solar radiation.

Because the requirements of mangroves for light are lower than the average levels of solar radiation in the region, mangroves are not expected to be sensitive to the projected changes in levels of solar radiation caused by a more intense hydrological cycle. During periods of high solar radiation, however, the absorption of light translates into heat energy, which can be expected to exacerbate the effects of higher temperature on water loss (Section 6.6.1.2).

Potential impact and adaptive capacity

The potential impact of altered solar radiation on mangroves is expected to be low, except where mangroves have high exposure to solar radiation combined with limited freshwater supply. These conditions occur, for example, on the leeward side of high islands such as Viti Levu and Vanua Levu in Fiji, and on the west coast of New Caledonia where total rainfall is projected to decline (Chapter 2). If slow rates of sea-level rise were to occur they may enhance the adaptive capacity of mangroves to increased exposure to light by increasing tidal flushing and freshwater supply. However, such slow rates are not expected and thus limited adaptive capacity is expected for mangroves which are exposed to high levels of solar radiation.

Vulnerability

Relative to other factors, the vulnerability of mangroves to projected changes in solar radiation is low, except in areas of combined high radiation and restricted runoff and tidal inundation, where vulnerability is expected to be moderate.

6.6.1.2 Temperature

Exposure and sensitivity

Mangroves in the tropical Pacific will be exposed to projected increases in air temperature and sea surface temperature (SST) of 0.5–1.0°C in 2035 for the B1 and A2 emissions scenarios, 1.0–1.5°C for B1 in 2100 and 2.5–3.0°C for A2 in 2100 (Chapters 2 and 3).

The sensitivity of mangroves to increased surface air temperature and SST is not well known[193] but is likely to be moderate. For example, *Rhizophora mangle* develops more silt roots per unit area when subjected to a 5°C increase in water temperature and produces more but significantly smaller leaves[194]. Also, young seedlings of a species of *Avicennia* are killed by water temperatures between 39°C and 40°C, although established seedlings and trees are not affected[16,180]. On the other hand, mangroves growing near coastal power stations show little or no visible effects from warmer effluent water[195].

Potential impact and adaptive capacity

Mangroves have a high degree of tolerance to heat stress compared with other plants[196]. Thus, even for the A2 scenario in 2100, the projected increases in air temperature are not expected to have substantial effects on the growth and survival of mangroves because the projected increases are below those known to cause detrimental effects. Respiration (CO_2 efflux) from plants and microbial communities in sediments approximately doubles with every 10°C increase in temperature, so that on hot days there would be reduced net carbon gain, increased methane emissions and decreases in soil carbon storage[26]. In addition, mangroves have a range of adaptations, such as reducing the apertures of their stomata, to cope with water loss induced by increased evaporation under heat stress[103,180].

Vulnerability

Mangroves are expected to have very low vulnerability to the projected increases in air temperature and SST. However, an indirect vulnerability to increases in SST may result from the projected decreases in coral cover due to thermal bleaching (Chapter 5), which are expected to reduce sediment supply to mangroves on low islands, and increase exposure to wave action.

Mangrove habitats can be important fishing areas

Photo: Nicolas Petit

6.6.1.3 Rainfall

Exposure and sensitivity

In equatorial areas of the Pacific, rainfall is expected to increase by 5–15% for the B1 emissions scenario and 5–20% for the A2 scenario in 2035, and by 10–20% in 2100 for both emissions scenarios (Chapter 2). In the subtropics, rainfall is projected to decrease by 5–10% for B1 in 2035, and by 10–20% for A2 in 2035 and for both scenarios in 2100 (Chapter 2). Extremes in wet and dry periods are likely to become more extreme, and droughts associated with the projected changes in rainfall are expected to be more intense due to the increase in temperature (Chapter 2).

Mangroves are expected to be moderately sensitive to these changes because soil salinity along the intertidal gradient is affected by the interaction of tidal inundation and rainfall. At locations with low rainfall and high evaporation, soil salinity in the upper intertidal gradient may be high, even though inundation is infrequent. On the other hand, where rainfall greatly exceeds evaporation, for example, in Kosrae, FSM[197], salinity levels do not build up in the soil, and soil salinity is negatively correlated with distance from the seaward edge of the mangrove habitat.

Potential impact and adaptive capacity

The effects of lowered salinity associated with increases in rainfall are likely to benefit mangrove ecosystems in equatorial areas, but are expected to be negative in the subtropics where decreases in rainfall (increases in salinity) are projected. Reduced runoff from catchments in New Caledonia may decrease the delivery of sediment to mangrove habitats near estuaries, making it more difficult for the trees at the seaward margins to accumulate sediment and adapt to rising sea levels[35]. Increased drought conditions may also reduce the flowering and fruiting of mangroves[186,187], and perhaps increase the areas of upper intertidal salt flats currently found in the drier areas of the region, such as the leeward side of Viti Levu in Fiji.

Depending on environmental conditions, mangroves can minimise water loss and maximise growth by using water more efficiently and reducing transpiration rates. Such physiological plasticity is one reason why mangroves are so successful across the intertidal seascape and these attributes may assist them to adapt to drier conditions. Too much fresh water also poses problems for mangroves. In stagnant flooded soils, roots of many mangroves develop a very thin, slightly oxidised zone that can effectively isolate the actively growing root area[198]. Seedlings without well-developed aerial roots would suffer more in this situation than mature trees.

Vulnerability

Mangroves are expected to have low to moderate vulnerability to the projected changes in rainfall, and subsequently salinity, under both scenarios in 2035, with some benefits to plant growth possible from increasing rainfall in equatorial areas. However, as rainfall changes are magnified over time, the vulnerability of mangroves will increase to moderate in 2100 under both scenarios, particularly in areas of the Pacific that experience declining rainfall.

6.6.1.4 Nutrients

Exposure and sensitivity

The projected changes in rainfall outlined above are expected to alter runoff patterns and the delivery of nutrients to mangrove habitats. Future changes in nutrient supply are hard to quantify because they will be related to the intensity of rainfall. However, increases in nutrients derived from runoff are expected in equatorial areas of the Pacific, and decreases in New Caledonia.

Nutrient enrichment enhances vertical accretion and surface elevation of mangrove forests through increased deposition of roots[161]. Where nutrients are limited, the responses of mangroves are complex; they differ across different types of mangrove forests or locations, depending on the availability of the various nutrients required[132,133]. For example, *Rhizophora mangle* in Belize is limited to different degrees by nitrogen and phosphorus, depending on the zone in which it occurs[131,199]. Below-ground decomposition is generally enhanced by additional phosphorus but not additional nitrogen[131]. In contrast, both nitrogen and phosphorus are limiting for mangroves in Florida, USA[133].

Potential impact and adaptive capacity

In equatorial areas, the addition of nitrogen and phosphorus is likely to increase plant productivity by altering both tree growth and nutrient dynamics, with the magnitude and pattern of response differing for different nutrients[131,132]. In general, increased nutrients may benefit mangroves, or assist them to adapt to rising sea levels[161,200]. But changes in nutrient delivery, when coupled with low rainfall, have the potential to affect mangroves negatively. For example, projected decreases in rainfall (e.g. New Caledonia) may be expected to increase mangrove mortality where nitrogen concentrations increase[201]. Ultimately, community composition could be affected, with different mangrove species surviving at different rates, depending on their requirements for nitrogen and phosphorous[131,133].

Mangrove roots provide shelter for fish at high tide

Photo: Gary Bell

Because mangroves have large nutrient and carbon stores in soils and plant biomass[202,203], small changes in nutrients alone are not likely to have significant effects. However, when a decrease in nutrients is coupled with increases in temperature and atmospheric CO_2 (and associated increases in respiration), negative effects on plant tissue balance may occur[204] (Section 6.6.1.6).

The adaptive capacity of mangroves to changes in nutrient delivery will mostly be at the community level, with different species dominating under different nutrient conditions, and community composition shifting accordingly. This will have implications for the diversity and structure of mangrove habitats[204], and the services they provide to fish and invertebrate species harvested by coastal fisheries.

Vulnerability

The effects of the projected increases in nutrient delivery on mangroves around high islands in the equatorial Pacific are likely to be positive. In contrast, mangroves in New Caledonia are expected to be negatively affected by the projected decreases in availability of nutrients. The vulnerability of mangroves in New Caledonia is assessed as low, however, due to their inherent adaptive capacity.

6.6.1.5 Cyclones and storms

Exposure and sensitivity

Although global climate models do not project an increase in the frequency of cyclones in the tropical Pacific, there is the possibility that cyclones and storms will become more intense within the cyclone belt over the remainder of this century. In particular, wind speeds associated with cyclones may increase by 1–8% for every 1°C rise in SST (Chapter 2).

Mangroves are sensitive to strong winds associated with cyclones and storms, which damage foliage, desiccate plant tissues, and increase evaporation rates and salinity stress[35]. The landward margin of mangroves is particularly prone to high evaporative loses and drying-out of the substrate. Increased wave surge during cyclones erodes sediments in the seaward mangrove zone and reduces the stability of plants normally provided by their root systems[64,80]. On the positive side, stronger winds may facilitate pollination of species such as *Rhizophora* and *Excocaria,* and the dispersal of seeds.

Potential impact and adaptive capacity

Under prolonged and severe wind conditions, evaporative losses may result in die-back of mangroves. Stronger wave surges are also likely to remove mangroves from the seaward edge of mangrove habitats. While the logs from fallen trees may provide some shelter for juvenile fish if washed into subtidal areas, losses in primary productivity can be expected to exceed such benefits in many places. The movement of large, woody debris in mangrove areas during high tide can also disturb establishment of seedlings.

After a cyclone, there is usually a narrow zone of damage to mangroves along the coast due to storm surge, and complete defoliation in the path of the storm. Mangrove species have different tolerances to cyclone damage[205]. Rhizophoraceae have low tolerance and cannot resprout from dormant buds, whereas species of *Avicennia* can resprout. Mortality of mangroves as a result of storms has led to collapse of peat soils and changed hydrological conditions[206]. In general, mangroves grow new leaves after cyclones and storms unless there is structural damage to the trees or burial of the roots by sediments. Over time, recruitment of seedlings occurs from adjacent undamaged areas, and the mangrove habitat is re-established. This natural adaptive capacity can be enhanced and accelerated by replanting programmes.

Vulnerability

Mangrove habitats in the tropical Pacific are considered to have moderate vulnerability to the effects of more intense cyclones. Damage is expected to occur during these high-energy events, but the trees should eventually recover from the effects of wind and waves, prolonged inundation and sediment deposition, where the physical conditions required for growth and survival are restored.

6.6.1.6 Carbon dioxide

Exposure and sensitivity

For the B1 and A2 emissions scenarios, atmospheric concentrations of CO_2 are projected to be ~ 400 ppm in 2035. By 2100, CO_2 levels are expected to be 450–500 ppm for B1, and 750–800 ppm for A2[207]. The projected levels of CO_2 are also expected to increase the acidity of the ocean, and reduce the availability of carbonate ions (Chapter 3).

The few studies on the impacts of elevated CO_2 on mangroves suggest that primary production of mangroves is likely to be enhanced under future climate change scenarios. In situations of increased moisture stress, enhanced CO_2 may also partially reduce the negative effects of reduced humidity and rainfall[208]. Increased levels of CO_2 may also change the patterns of species dominance and accelerate mangrove encroachment into adjacent inland brackish and freshwater environments. However, when increases in CO_2 are combined with higher temperature and nutrient levels, there may be negative effects on plant tissue balance (Section 6.6.1.4).

Potential impact and adaptive capacity

The projected increases in atmospheric CO_2 are expected to increase productivity of mangroves, provided that salinity and humidity are also conducive to tree growth. The increased acidification of the ocean is not likely to affect mangrove habitats greatly, although the process by which dissolved calcium from dead shells makes some brackish waters alkaline may be weakened as acidification increases. Even if soil acidity increases, however, mangroves are not expected to be affected adversely, because many mangrove soils are neutral to slightly acidic due to sulphur-reducing bacteria and the presence of acidic clays[162]. In Malaysia, mangroves occur in very acidic brackish waters, probably due to the aeration of soil sulphates, forming sulphuric acid.

A common plant adaptation to elevated CO_2 concentrations is decreased nitrogen investment in leaves and a concomitant increase in the carbon:nitrogen ratio of plant tissues[209]. If mangroves respond in this way, the changes in plant tissue balance will have knock on effects for food webs[210], and on nutrient cycling[211].

An indirect impact of increased ocean acidity on mangrove systems could be reduction in the supply of carbonate sediment, expected to result from reduced rates of calcification by corals (Chapter 5). This may reduce the ability of mangroves on low islands to adapt to sea-level rise.

Vulnerability

Mangroves are unlikely to suffer negative effects as a result of increased atmospheric CO_2 alone. Rather, they are expected to grow faster and become carbon sinks in some places. There may also be increased allocation to below-ground biomass with elevated CO_2, resulting in greater gains in soil surface elevation and stability under sea-level rise[212]. In some locations, synergies with increased temperature and altered nutrient delivery may result in negative effects on plant tissue balance. In such places, mangroves are likely to have a very low to low vulnerability to elevated CO_2.

6.6.1.7 Sea level

Exposure and sensitivity

The conservative projections for sea-level rise made in the IPCC Fourth Assessment Report (IPCC-AR4) of ~ 10 cm for the B1 and A2 emissions scenarios in 2035, ~ 20–40 cm for B1 and ~ 20–50 cm for A2 in 2100, have now been increased substantially. More recent estimates are 20–30 cm for the B1 and A2 scenarios in 2035, 70–110 cm for B1 and 90–140 cm for A2 in 2100 (Chapter 3).

Mangroves grow between mean sea level and mean high water, and the zonation of mangrove species (**Figure 6.1**) is determined by inundation frequency controlled by the tides. If the tidal conditions under which mangroves grow are altered, the growth and survival of the trees are affected. In experiments to simulate the effects of inundation due to sea-level rise on the growth of *Rhizophora mangle*, for example, seedlings maintained under conditions where an increase of 16 cm was imposed on normal tidal water levels were 10–20% smaller than control plants after 2.5 years[213].

Potential impact and adaptive capacity

The projected rise in sea level could potentially have a powerful effect on mangroves. However, where mangroves can continue to accumulate sediments at appropriate rates, the effects are likely to be less severe. The capacity of mangrove forests to resist sea-level rise is likely to depend on the source of sediment, and the rate of sedimentation, which in turn is influenced by rainfall, tidal amplitude, coastal currents and wave energy[214]. Biogenic processes, particularly root growth rates, will also be important in the response of mangroves to sea-level rise[161].

Sedimentation is expected to be slower in areas of natural subsidence, such as southern PNG, American Samoa and western Viti Levu in Fiji[178,179,215]. Mangroves on low islands may be able to compensate for low rates of sea-level rise through accumulation of peat[161,182]. Most continental and high island mangroves are expected to adapt if the rate of sediment deposition exceeds the rate of sea-level rise. However, various surface and subsurface processes, such as sediment accretion and erosion, biotic contributions, below-ground primary production, sediment compaction, fluctuations in water-table levels and pore water storage, make sedimentation rates alone a poor indicator of mangrove responses to rising sea level[216,217].

The potential impact of sea-level rise on mangroves will be greatly reduced in those locations where they can migrate landward[217]. The scope for migration will depend on the rates of sea-level rise and accumulation of sediments, and changes in elevation. Historical records show mangrove die-back under accelerated rates of sea-level rise, followed by re-establishment as sea level falls (**Figure 6.8**). Landward migration will, however, be constrained in many locations by barriers such as coastal roads and settlements, and where steep terrain occurs behind mangroves. In addition, the projected acceleration in the rate of sea-level rise after 2050[207] is expected to make it difficult for mangroves to re-establish and reach reproductive maturity before their intertidal elevation envelope is reduced again. PNG, Solomon Islands and FSM have freshwater swamp forest or marsh on the landward margin of mangroves that could become mangrove habitat with rising sea level.

Thus, establishment of mangroves in new landward areas is only likely where (1) the topography is suitable for colonisation, (2) the rate of sea-level rise is compatible with the life cycles of mangrove species, (3) the hydrology and sediment composition is suitable, and (4) there is limited competition with non-mangrove species[214,217].

Vulnerability

The vulnerability of mangroves to projected sea-level rise is high for both scenarios in 2035, particularly in locations where the coastline is subsiding and sedimentation rates are low. Vulnerability is expected to be very high for both B1 and A2 scenarios in 2100 where landward migration is blocked by infrastructure, where there is intensive land use and steep gradients, and as the magnitude of sea-level rise increases later in the century.

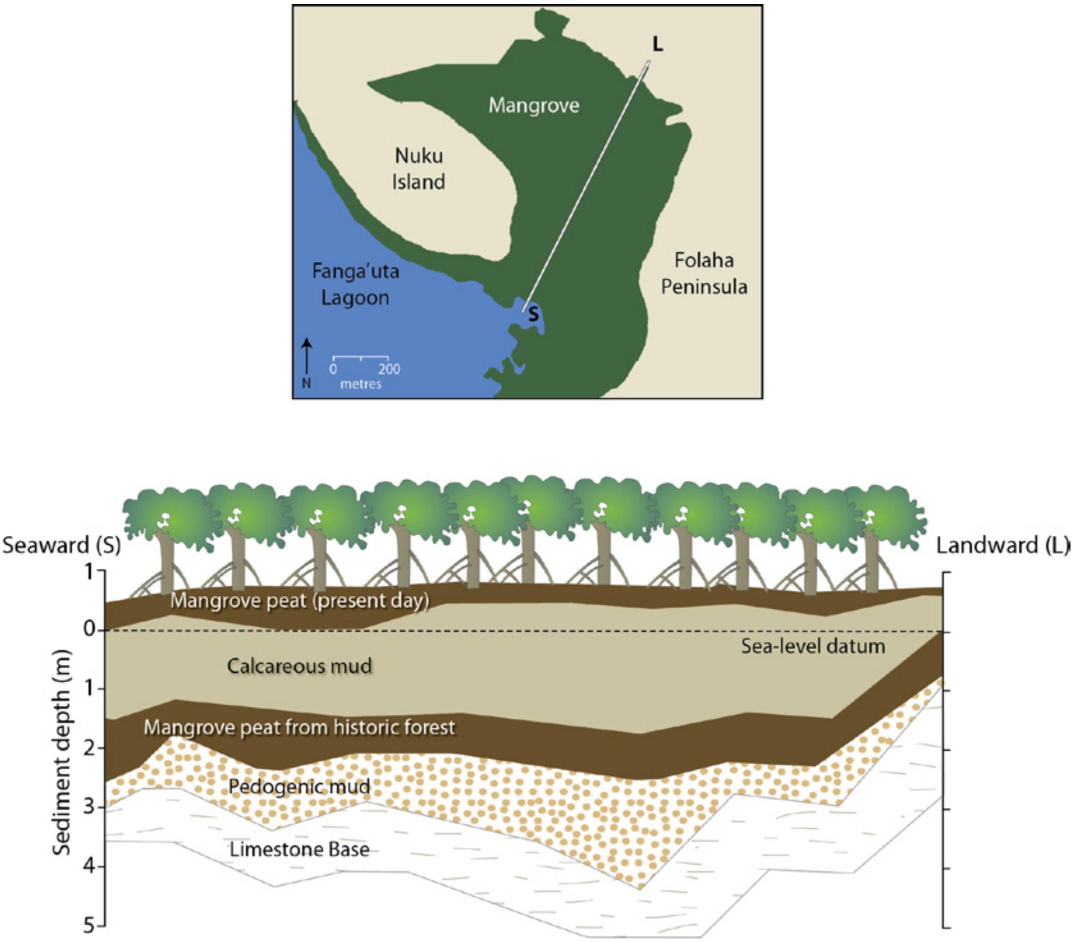


Figure 6.8 Sedimentary evidence of the extent of mangroves at Folaha, Tongatapu, Tonga, 7000–5500 years ago when forests growing 1.5–2.5 m below present sea level were exposed to accelerated sea-level rise (1.2 mm per year). The mangroves died back to create a lagoon, ultimately re-establishing after a fall in sea level[181].

6.6.2 Seagrasses

6.6.2.1 Solar radiation

Exposure and sensitivity

Seagrass habitats in the tropical Pacific are expected to be exposed to reductions in light as a result of climate change. The projected increases in rainfall (Section 6.6.1.3) (Chapter 2), are likely to reduce the availability of light by < 1–15% in 2035 and 5–20% in 2100 due to (1) increased turbidity of coastal waters from higher levels of runoff from high islands (Chapter 7); (2) greater growth of phytoplankton and epiphytic algae from the associated nutrients; and (3) a possible increase in the percentage of cloudy days due to intensification of the hydrological cycle (Chapter 2). No reduction in availability of light is expected for the large areas of seagrass habitat in New Caledonia due to the projected decreases in rainfall of 5–10% by 2035 and 5–20% by 2100 (Chapter 2). Indeed, increases in the number of cloud-free days are likely to occur there in winter.

The seagrasses found in the tropical Pacific have varying tolerances to low levels of light, and grow at different depths (**Figure 6.9**). These species are sensitive to reduced levels of light because the resulting decreases in photosynthesis affect growth rates. In extreme cases where carbon reserves are depleted and respiration demand outstrips photosynthesis, plants will die[111,142,218–223]. Light limitation, caused by suspended sediment and excess nutrients, has a major impact on seagrass meadows[218,224].

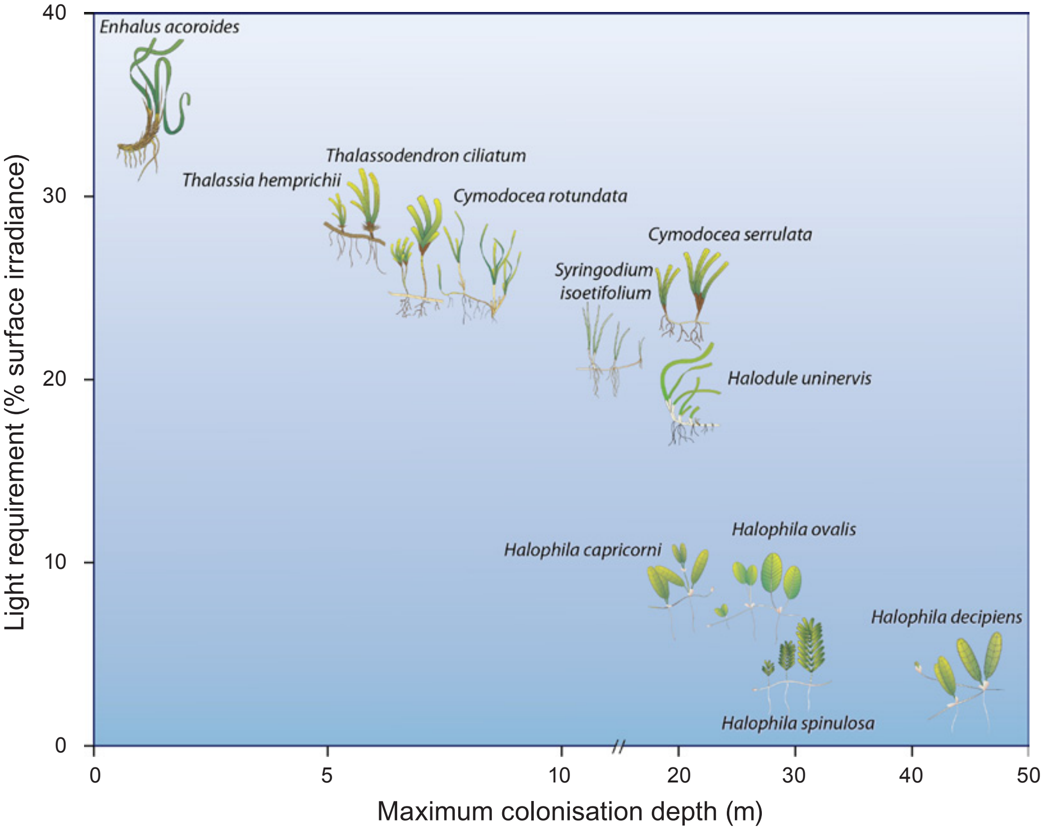


Figure 6.9 Estimated light requirements and maximum depth limit of various seagrass species in the tropical Pacific (source: Collier and Waycott 2009)[4].

The mechanisms that seagrasses use to recover from periods of reduced light are species-specific[43,225–227] and vary due to differences in the morphological plasticity, storage products, life-form and growth rates of species[109]. In general, morphologically large and slow-growing species, such as *Thalassia* spp., tolerate prolonged periods of low light but are slow to recover if severely affected. In contrast, small rapidly-growing species, such as *Halophila* spp., cannot tolerate extended periods of low light because of limited storage reserves. They can recover from such impacts quickly if conditions improve, however, by regenerating through seed production and rhizome extension[221].

The response of seagrasses to reduced light is rapid. When seagrasses from the Pacific were exposed to low light levels (< 14% incident light), the rate of leaf extension changed within 7 days, and significant losses of leaves per shoot occurred after 14 days[221,228,229]. After 46 days, shoot density was reduced and complete loss of shoots was predicted after 100 days.

Seagrasses may also be affected by over-exposure to UV irradiance[230]. High levels of UV reduce production of chlorophyll *a* and enhance production of anthocyanins (vacuolar pigments), causing 'reddening' of plant leaf tissues[230].

Potential impact and adaptive capacity

Changes in solar radiation are expected to have profound effects on seagrasses in the tropical Pacific, ranging from changes in the relative abundance and species composition of species, including loss of large, slow-growing species where exposure to low light levels are severe and prolonged, to changes in leaf colour where exposure to UV increases. Significant losses to the area of seagrass meadows are expected to occur where light availability is reduced for long periods (~ 100 days)[221]. Possibly up to 20% of seagrass area in the region could be lost by 2100 due to light reduction alone. Such losses are expected to occur mainly in locations with significantly higher rainfall, where the resulting turbid conditions persist for months.

Seagrasses are able to respond to shorter-term (days to weeks) reductions in light through a range of morphological and physiological adjustments[2]. When the factors limiting light are removed, and if the seagrasses have not completely drained their reserves, they can recover from vegetative fragments left in the meadows. If whole meadows have been lost, then recovery can only occur through recruitment of seedlings. Seagrass communities comprising small species, such as *Halophila* spp. and *Halodule* spp., have a greater capacity for recovery, because they produce copious quantities of seed and have rapid colonisation rates due to their growth form[4,43].

Vulnerability

The seagrasses expected to be most vulnerable to changes in light conditions are those that occur in estuaries or in coastal habitats subject to runoff. Vulnerability is expected to be moderate in 2035 and 2100 for most locations, increasing to high around islands with large, steep catchments, where runoff remains in bays and lagoons for long periods. Complete loss of seagrass is expected to occur if turbidity and light reduction persist at below the minimum light requirements for periods > 100 days[221,229].

6.6.2.2 Temperature

Exposure and sensitivity

Seagrasses in the tropical Pacific are projected to be exposed to increases in SST in the range of 0.5–1.0°C in 2035 for the B1 and A2 emissions scenarios, 1.0–1.5°C for B1 and 2.5–3.0°C for A2 in 2100 (Chapters 2 and 3).

Seagrasses are likely to be highly sensitive to increases in SST, whether they occur as short-term 'spikes' in maximum temperature over periods of hours, or as chronic exposures for weeks or months, because in many locations seagrasses are already growing at their maximum temperature tolerance[122,229]. Short-term exposure to temperatures > 40°C causes death of seagrass leaves. Such effects have been recorded regularly for the tropical seagrass meadows of the region[231]. However, there is a wide range of responses to short-term increases in temperature > 40°C among seagrasses, with death of leaves occurring more rapidly for the smaller species[122,229] (**Figure 6.10**).

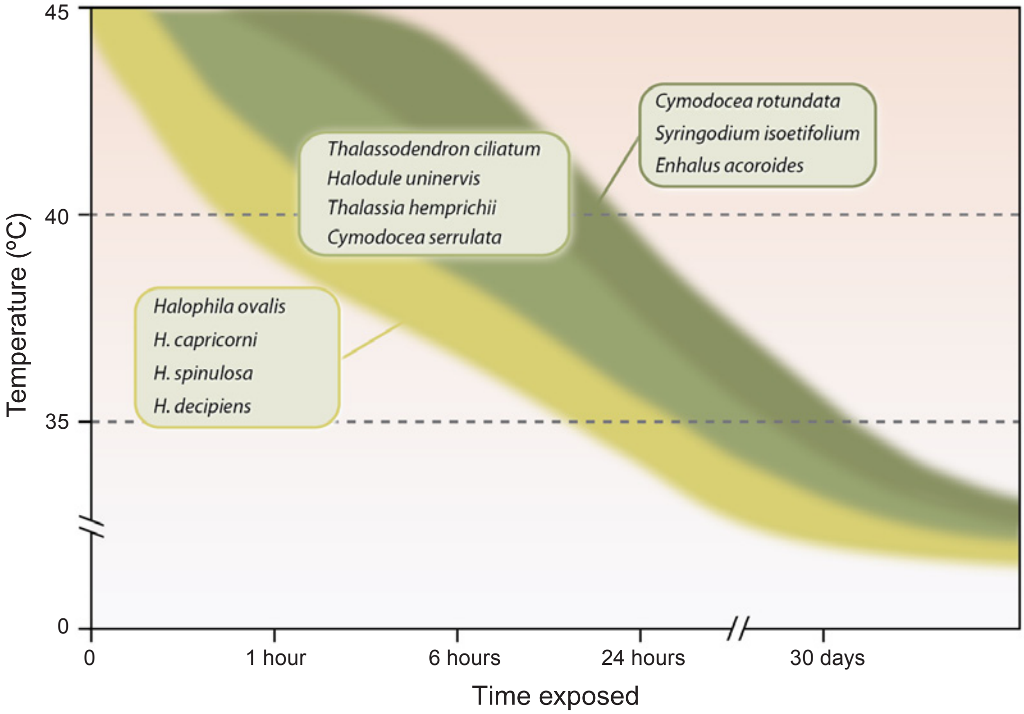


Figure 6.10 Thresholds for survival of seagrass species in the tropical Pacific under elevated sea surface temperatures (SST) and increasing exposure. Species of *Halophila* are the most sensitive to high SST, and *Cymodocea rotundata* and *Syrigodium isoetifolium* are the most tolerant (source: Campbell et al. 2006, Collier unpublished data)[122]. Note, however, that all species shown here can co-exist throughout the region and may have similar long-term (> 30 days) temperature thresholds.

Chronic elevated SST of up to +3°C results in increased respiratory demand and loss of seagrasses when respiration outstrips photosynthesis[229]. Once again, responses are likely to be species-specific, although data on the effects of chronic temperature stress for tropical seagrasses are limited.

Potential impact and adaptive capacity

The projected increases in SST are expected to cause changes in the species composition, relative abundance and distribution of seagrasses in the tropical Pacific. Short-term temperature 'spikes' are likely to reduce biomass through 'burn off', whereas overall increases in SST are expected to drive the more chronic changes in species composition (structural complexity) and distribution[229]. The fact that the roots and rhizomes of seagrasses are buried in sediments, offers some protection against the impacts of short-term changes in SST. However, as seagrasses possess high light requirements[111], their ability to adapt to longer-term increases in SST will be limited by their overall respiration demand[229]. Thus, the impact of increasing SST will depend on light availability, with interactions between elevated temperatures and reduced light levels resulting in greater potential impacts. Where seagrasses are not stressed by light, temperature may become the primary driver for responses by seagrasses. However, because seagrasses are typically light-limited, light levels are expected to continue to dominate their responses to changing environmental conditions.

Vulnerability

Many of the seagrass meadows in the region are expected to have moderate to high vulnerability to increases in SST. Shallow intertidal seagrass meadows are likely to be at the greatest risk, particularly where the less robust *Halophila* spp. and *Halodule* spp. dominate. Where seagrasses are already experiencing lower light levels, meadows will have high vulnerability to increases in SST because their relatively high respiration demands are expected to exceed their capacity for gaining carbon through photosynthesis.

6.6.2.3 Rainfall

Exposure and sensitivity

In the equatorial areas of the Pacific, rainfall is projected to increase by 5–15% for the B1 emissions scenario and 5–20% for the A2 scenario in 2035, and by 10–20% in 2100 for both emissions scenarios (Chapter 2). In the subtropics, rainfall is expected to decrease by 5–10% for B1 in 2035 and by 10–20% for A2 in 2035 and both scenarios in 2100 (Chapter 2). Extremes in wet and dry periods are also projected to become more extreme.

In addition to affecting light, greater runoff from higher rainfall is expected to reduce salinity and increase the transfer of sediments, nutrients and toxic chemicals from catchments to seagrass meadows. Strong reductions in salinity inhibit the growth of seagrasses[145]. However, the effects of salinity are usually localised, being more significant in bays and lagoons where the residence times of water are in the order of weeks to months.

Seagrasses are sensitive to the deposition of sediments because physical burial prevents their ability to grow[21,22,49,219,222,232]. Modest additions of sediments can benefit seagrass habitats through provision of new substrate and the addition of nutrients. However, where deposition rates are greater than the ability of seagrass to grow through the new sediments, plants will die. Movement of sediments can also cause scouring of seagrass habitats[3], with damage being proportional to sediment loads and the volume of runoff. Scouring of seagrasses has been a problem in Pohnpei[233]. Chemical pollutants such as diuron, known to be poisonous to seagrasses, have been documented to occur in tropical seagrass sediments[234]. Where chemical pollutants are present, the effects are generally proportional to sediment loads and the volume of runoff. The effects of variation in nutrient loads on seagrasses are discussed in Section 6.6.2.4.

Potential impact and adaptive capacity

The potential effects of changes in rainfall on seagrass habitats are complex, but expected to be significant in several PICTs. The greatest impacts are likely to occur around high islands in the tropics, where runoff and sediment loads are projected to increase in the future. Intertidal seagrass habitats close to land are likely to be affected more severely than subtidal meadows because they are directly exposed to both rainfall and runoff. Particularly significant impacts are expected where soil erosion associated with coastal agriculture (e.g. palm oil plantations), land clearing (e.g. logging and mining) and mine tailing discharge occurs (Chapter 7).

The capacity for seagrass habitats to adapt to reduced salinity will be correlated to the species that occur in each region. Some species, such as *H. ovalis*, have broader salinity tolerances[235] and are likely to become more prevalent in lower salinity environments. Limited adaptive capacity is expected among species that do not tolerate freshwater flushes, although research is still needed to identify the thresholds and responses of species. Similarly, seagrasses are unlikely to have much adaptive capacity to pollution, which is expected to have a cumulative effect on the plants. Low chronic loads of some toxins have been reported to have a positive effect on plant growth. However, further research is needed to identify specific plant responses, in particular the relationship between toxicant loads and seedling germination and growth[3].

Vulnerability

The large seagrass habitats in nearshore bays and lagoons around high islands in the tropics are expected to have a moderate to high vulnerability to reductions in salinity and increases in sediments and toxic chemicals resulting from increased rainfall and runoff. Seagrasses in New Caledonia are expected to have low vulnerability to future patterns of rainfall, providing that future management can ensure that runoff from mining activities does not damage the plants.

6.6.2.4 Nutrients

Exposure and sensitivity

The projected changes in rainfall described immediately above are also expected to change the availability of nutrients in seagrass habitats because of altered runoff patterns. As outlined in Section 6.6.1.4, changes in supply of nutrients are hard to quantify, but increases in equatorial areas, and decreases in New Caledonia, are expected.

A tropical seagrass habitat

Photo: Andre Seale

In general, seagrass meadows throughout the tropical Pacific occur in reef-associated, carbonate-dominated sediments and are phosphorous limited (Sections 6.2.2 and 6.4.3). Delivery of additional phosphorus, nitrogen and other micronutrients through increases in runoff is expected to enhance seagrass growth. However, elevated concentrations of nutrients in the water column are also expected to result in increases in epiphytic algae on seagrass leaves[236]. These algae block light, retarding the growth of seagrasses[111]. They also increase the resistance of leaves to water movement and can be expected to increase the loss of leaves during storm surge.

Potential impact and adaptive capacity

The height and density of seagrass leaves, and the area of seagrass, could potentially increase under the influence of more nutrients where nutrients are limiting[130,139,140]. However, where other factors limit seagrass growth, the potential for seagrass habitats to benefit from increased nutrients will not be realised. For example, in areas where increased runoff reduces salinity and/or water clarity in coastal waters for extended periods (i.e. in bays and 'ponded' lagoons with high residence times), e.g. parts of Marovo and Roviana Lagoons in Solomon Islands, seagrass growth is unlikely to increase. The inhibiting effects of turbidity are expected to be common in those catchments where agriculture, forestry and mining have not been managed to minimise runoff (Chapter 7). The potential effects of increased epiphytic algae may be reduced where herbivorous invertebrates and fish are common. This may rarely occur, however, because increased nutrient loads are likely to be associated with areas under active development and fishing pressure can also be expected to be more intense in such places (Chapter 9).

The seagrass habitats of New Caledonia are not expected to benefit from increased nutrients because of projected reductions in rainfall. However, the possibility of more intense rainfall events and cyclones means that local areas may periodically receive excessive nutrients (and sediments) due to increased rates of removal of drier topsoil and reduced catchment vegetation when these events do occur (Chapter 7).

In locations where nutrient concentrations are relatively low, and where light is not limiting, seagrasses have the capacity to absorb increased nutrient levels and increase their biomass[130]. Higher nutrient loads may also increase nutrient concentrations in tissues[140], to the point where the plants are unable to use or store any more nutrients and where other factors become limiting. When nutrient loads exceed the ability of seagrasses to use them given the available light, blooms of epiphytic algae occur, further reducing light availability[111].

Vulnerability

Modest increases in availability of nutrients is expected to have a small positive effect on seagrass habitats in the tropical Pacific. Where levels of runoff and nutrients are high, the potential benefits will be over-ridden by the adverse effects of low salinities, reduced light due to turbidity or algal blooms and, in poorly managed catchments, the effects of chemical pollutants. Such problems are expected to be more pronounced under the A2 scenario in 2100, when seagrasses are likely to have low to moderate vulnerability to the combined impacts of altered nutrients, salinity and turbidity.

6.6.2.5 Cyclones and storms

Exposure and sensitivity

As outlined in Section 6.6.1.5, cyclones and storms may possibly become more intense within the cyclone belt over the remainder of this century (Chapter 2). In addition to increasing sediment loads and nutrient levels, more intense cyclones and storms are expected to increase the power of waves affecting coastal habitats (Chapter 3).

Wave surge strips leaves from seagrasses and often uproots the subsurface rhizomes, removing the plants from large areas of the intertidal and shallow subtidal zones[3]. Reductions in light caused by greater turbidity following cyclones can also be expected to affect seagrasses[219].

Succession in species composition of seagrasses is expected to occur in those areas where cyclones remove plants[4,237]. Small species (e.g. *Halophila ovalis* and *Halodule uninervis*) would be expected to dominate initially and then be replaced gradually by the larger, climax species (e.g. *Cymodocea serrulata*, *Thalassia hemprichii* and *Enhalus acoroides*). Note, however, that this succession does not usually proceed to a fully stable community in locations where other factors, such as reduced light, limit the colonisation by structurally large species. Such moderate levels of disturbance generally result in seagrass communities being dominated by smaller species of seagrass[4].

Potential impact and adaptive capacity

Severe storms can devastate seagrass habitats through the combined effects of physical disturbance, reductions in light and salinity, and movement of sediments. Such impacts are expected to be greatest in shallow, subtidal and intertidal areas because they receive the full force of wave energy (Chapter 3). However, the degree of change to seagrass habitats due to the more moderate effects of cyclones and storms depends on the species composition of the meadow. Small seagrasses, such as *Halophila* spp. or *Halodule uninervis*, are likely to suffer more damage than larger species with rhizomes buried deeper into the sediment, such as *T. hemprichii*.

Vulnerability

Intertidal and shallow subtidal seagrasses are expected to be highly vulnerable to any increase in cyclone intensity. The effects of wave surge on seagrass habitats in the path of a cyclone are likely to be devastating, except for seagrasses growing in relatively deep water (Section 6.2.2.5). In addition, scouring by mobile sediments associated with high energy water movements would significantly affect seagrass meadows. Small species of seagrass are expected to be more vulnerable than large species in areas where the physical effects of cyclones and storms diminish away from the trajectory of the storm. However, because these species also have the capacity to recover rapidly[4], the effects may only be short-term provided propagules are available to re-establish the meadows.

6.6.2.6 Carbon dioxide

Exposure and sensitivity

Future emissions of CO_2 are projected to reduce the pH of the tropical Pacific Ocean by 0.1 units by 2035, and by 0.2 to 0.3 units by 2100 for the A2 emissions scenario (Chapter 3). All seagrass meadows will be directly exposed to these declines in pH.

However, the pH in seagrass meadows can vary by up to 0.9 units over diurnal cycles as a direct result of carbon uptake by seagrasses and other autotrophs (including epiphytic algae). The largest changes in CO_2 concentrations occur during the day, when photosynthesis is at a maximum, and in shallow water[238–241].

The most critical effect of increases in CO_2 concentration and reductions in pH for seagrasses relate to changes in the availability of dissolved inorganic carbon, and the rate at which the plants take up dissolved inorganic carbon. Seagrasses use both HCO_3^- and CO_2, with HCO_3^- requiring conversion to CO_2 at some stage, either external to the leaf (within the boundary layer) or after uptake[235]. Seagrasses obtain about 50% of their dissolved inorganic carbon from HCO_3^-; the remainder coming from direct CO_2 uptake[242–244]. The photosynthetic rates of seagrasses are currently limited by the availability of CO_2 at the present-day average pH of 8.2 but higher concentrations of CO_2 at lower pH result in faster photosynthetic rates[242,243,245,246]. In the temperate seagrass *Zostera marina*, higher photosynthetic rates at lower pH for one year are translated into increased productivity and reproductive output[247]. These findings are consistent with the evolution of seagrasses at a time of higher CO_2 concentration[224].

If changes in dissolved inorganic carbon alone are considered, seagrasses could benefit from projected increases in CO_2 concentrations[248]. However, there are differences among seagrass species in their uptake mechanisms and sensitivity to higher CO_2 concentrations[246]. These differences could affect the species of seagrass within meadows and the value of the habitat.

Calcifying epibiota growing on seagrass leaves, including foraminifera, bryozoa, spionid polychaetes and algae, are expected to be sensitive to changes in pH, with reductions in calcification and growth occurring at reduced pH[249,250]. Although the abundance of these calcifying organisms may be reduced on seagrass leaves, elevated CO_2 could enhance photosynthetic rates in non-calcifying epiphytes[249] and the total coverage of epibiota may not be altered significantly.

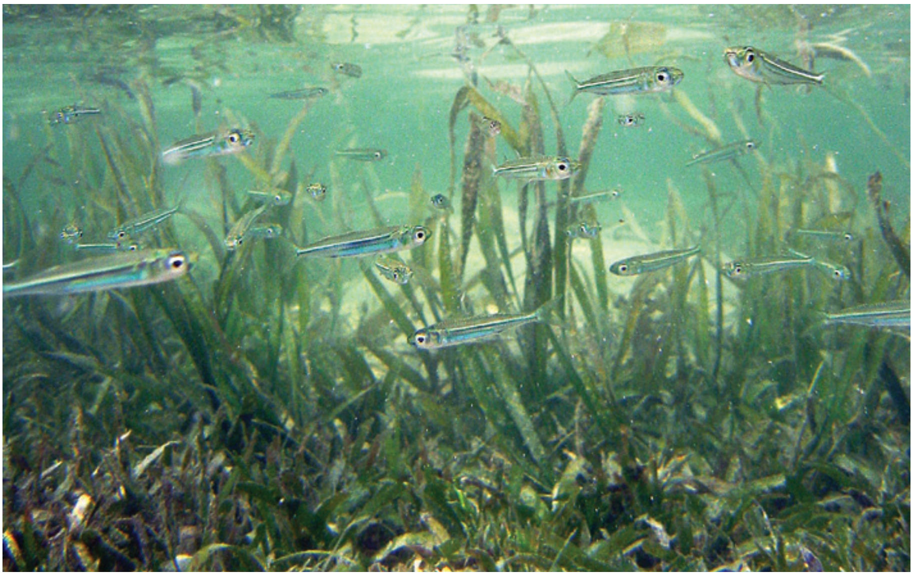
Potential impact and adaptive capacity

The most likely effects of elevated CO_2 on seagrasses will be increases in their productivity, biomass and reproductive output[247]. Higher CO_2 can also reduce the amount of light-saturated photosynthesis required to meet daily carbon budgets[245]. This should allow seagrasses to colonise deeper areas with lower light. However, differences in the sensitivity of seagrass species to elevated CO_2[246] could result in some seagrasses benefiting more than others. Any notable effect on seagrasses of changes in the epibiota on their leaves caused by increased CO_2 concentrations is unlikely.

The greater projected productivity of seagrasses, and the changes in their species composition, under higher levels of CO_2 are expected to flow-on to increase the ecosystem services provided by seagrasses in places where other impacts are minimised. In particular, the richness and productivity of food webs supported by seagrasses may increase, and the shelter that the plants provide for juvenile fish and invertebrates (Section 6.3.2) may be enhanced.

Vulnerability

Seagrasses are not expected to be vulnerable to increasing concentrations of CO_2. Instead, the effects of such increases on seagrass meadows in the tropical Pacific are expected to be higher photosynthetic rates, and greater productivity, biomass and reproductive output.



Seagrasses provide important habitats for small fish

Photo: Len McKenzie

6.6.2.7 Sea level

Exposure and sensitivity

The most recent estimates for future sea-level rise are considered to be 20–30 cm for the B1 and A2 emissions scenarios in 2035, 70–110 cm for B1 and 90–140 cm for A2 in 2100 (Chapter 3). Typically, seagrass habitats are limited by light availability on their deeper edges and should be sensitive to projected sea-level rise, with the increased depth likely to reduce light to the point where some of the deepest plants may not survive[3].

Surveys of seagrasses throughout the tropical Pacific have not generally estimated the proportion of meadows likely to be limited by light at the deeper edges of their distributions. As a result, we cannot determine the percentage of habitat exposed to sea-level rise. However, some seagrass species, e.g. *Halophila decipiens*, have a greater tolerance for lower light conditions and so the species composition, or relative cover of species at the deeper margins of meadows, i.e. their lower depth limit, may shift in favour of such species as sea level rises[49].

Potential impact and adaptive capacity

The expected rises in sea level are likely to result in the loss of seagrass cover or changes in species composition along the seaward edges of deeper meadows. Species growing on the deeper margins of seagrass habitats are likely to be at the limit of their light tolerance range and unable to adapt to further reductions[3] in light. In other parts of the meadows, however, the structure of the seagrass canopy is likely to change through the varying responses of species to reduced light[2,3,221]. This shift in composition is expected to be towards species with lower biomass. The effects of such changes on the ecosystem services provided by seagrasses to coastal fisheries have not been studied in the tropical Pacific, although the influence of changes to leaf height and density of seagrasses on fish and invertebrate communities have been described for temperate areas[251].

Seagrasses are capable of growing both vertically and horizontally and are expected to adapt to rising sea levels by growing landward in pace with their upper depth limit, provided the newly inundated sediments are suitable[3]. Coastal developments, such as rock walls or groynes, would prevent the potential colonisation of suitable habitat. Colonisation of newly inundated habitat will also be limited where the accretion of sediments favours establishment of mangroves.

Vulnerability

Seagrass meadows are estimated to have moderate vulnerability to sea-level rise where their depth is limited by light, and where expansion landward is blocked. Elsewhere, seagrass habitats are expected to have low vulnerability to sea-level rise.

6.6.3 Intertidal flats

The aspect of projected climate change of greatest relevance to intertidal flat habitats is sea-level rise. As outlined in Chapter 3, intertidal flats are expected to be exposed to rises in sea level of 20–30 cm for the B1 and A2 scenarios in 2035, 70–110 cm for B1 in 2100, and 90–140 cm for A2 in 2100. Intertidal flats are likely to be highly sensitive to these changes where this habitat cannot expand landward, or where rates of sedimentation do not keep pace with sea-level rise. Indeed, considerable losses of intertidal flats are expected to occur as a result of permanent inundation.

The potential impacts of the exposure of intertidal flats to sea-level rise are permanent changes to BMA communities and the associated epifauna and infauna. Many intertidal species preferentially inhabit vertical zones corresponding to subtle changes within the intertidal area above or below mean sea level[58]. The relationship between sediment surface height and average sea level is expected to be disturbed by ongoing sea-level rise. Consequently, gradual shifts in composition and/or abundance of intertidal BMA communities, epifauna and infauna are expected. In turn, this is likely to have significant knock on effects on the fish and invertebrates harvested from intertidal flats. In particular, permanent inundation of intertidal flats will allow continuous access by demersal fish species and exclude species that forage at low tide (e.g. birds and crabs). Benthic microalgae communities and fauna now common in the subtidal zone can be expected to gradually colonise permanently submerged intertidal areas. The new shallow subtidal zones created by rising sea levels may be ecologically challenging environments, with low water exchange and large temperature and salinity fluctuations.

A sea-level rise of 50 cm is expected to permanently inundate intertidal flats in PICTs with micro-tidal conditions (e.g. parts of Cook Islands), whereas a rise of ~ 1 m would be needed to permanently inundate the greater proportion of existing intertidal flats in PICTs with larger tidal ranges (e.g. central Pacific atolls). Although this is a simplistic analysis, species which have a strong dependence on a functioning intertidal flat habitat are expected to be gradually forced landward until they can no longer migrate. The burrowing crabs *Uca* spp., which feed when they emerge from their burrows at low tide, provide an example of the expected effects of sea-level rise on intertidal species. These crabs are restricted to upper intertidal flats where there is adequate time between tides for them to emerge and feed on sediments with the necessary moisture content – *Uca* spp. scrape the upper layers of sediment, filter BMA, meiofauna and detrital material, and then deposit balls of 'cleaned' sediment 3–4 mm in diameter. Changes in the appropriate levels of moisture in the sediment, and the time between falling and rising tide due to sea-level rise, will probably displace these species.

Intertidal flats, Tarawa Island, Kiribati

Photo: Tony Falkland

Progressive replacement of species dependent on intertidal flats may occur due to colonisation by species adapted to permanent submergence, but a loss of biodiversity is also expected. The impacts of such losses on subsistence fishing communities in the region will vary based on their dependence on these habitats. In some PICTs, intertidal gleaning is one of the main ways that low income urban and rural families secure dietary protein because they do not have the equipment or skills to catch fish. In other locations, collection of intertidal species is less important, because they are not a traditional component of the diet, or because harvests are already reduced from over-exploitation or pollution (Chapter 9).

6.7 Integrated vulnerability assessment

6.7.1 Mangroves

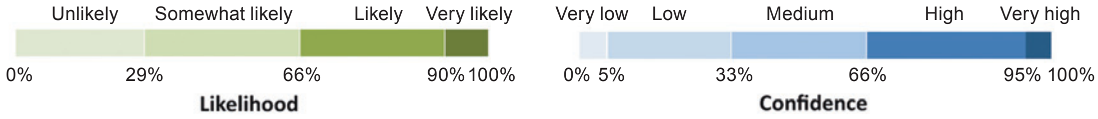
The projected changes in solar radiation, temperature, rainfall, nutrients and CO_2 are expected to have minimal effects on mangrove habitats in the tropical Pacific and, in principle, could work together to increase growth and productivity. However, these potential benefits are likely to be negated by the adverse effects of sea-level rise (**Table 6.4**). The projected rates of sea-level rise are expected to cause mangroves on the seaward fringes of their habitats to retreat[180] because they are unlikely to be able to accumulate sediments or produce sufficient root biomass to contribute to soil volume at the same rate as the rise in sea level[29] (Section 6.6.1.7). Even where rates of sedimentation are high, there is no guarantee that mangroves will survive because many species are intolerant of rapid sedimentation[252]. Thus, mangroves are likely to incur inundation stress in low intertidal positions, leading to reduced productivity, mortality and reduced forest area.

Mangroves have the potential to adapt in many areas by migrating landwards[179,180] (Section 6.6.1.7) but the maintenance of mangrove habitats through this process will depend on the rate of sea-level rise. If the rate accelerates, as projected (Chapter 3), migrating mangroves are unlikely to be able to escape the stress of inundation. Mangroves located where sedimentation rates are low, e.g. in places remote from river discharge, are expected to be particularly vulnerable. Mangroves in New Caledonia may be more vulnerable than those elsewhere in the region because not only will the projected decreases in rainfall reduce the supply of sediment, the lower precipitation may also increase salinity stress.

When the effects of changes to all the various features of the environment are integrated, mangroves are expected to have moderate vulnerability to climate change for the B1 and A2 emissions scenarios in 2035, increasing to a high vulnerability for B1 in 2100, and a very high vulnerability for A2 in 2100 (**Table 6.4**).

Table 6.4 Summary of the projected effects of climate change variables on mangrove and seagrass habitats in the tropical Pacific for the B1 and A2 emissions scenarios in 2035 and 2100 (based on the information in Sections 6.6.1 and 6.6.2), together with an assessment of the overall vulnerability of mangrove and seagrass habitats by integrating these effects. The likelihood and confidence associated with the integrated vulnerability assessments are also indicated. Note that the projected effects of each climate change variable can be negative (-) or positive (+); nil = no projected effect.

Scenario	Variable							Integrated vulnerability
	Light	Temp.	Rainfall	Nutrients	CO_2	Cyclones	Sea level	
Mangroves								
B1/A2 2035	Low (-)	Very low (-)	Low (+/-)	Low (+/-)	Very low (+/nil)	Moderate (-)	High (-)	Moderate 🟩 🟦
B1 2100	Low (-)	Very low (-)	Moderate (-)	Low (+/-)	Very low (+/nil)	Moderate (-)	Very high (-)	High 🟩 🟦
A2 2100	Low (-)	Very low (-)	Moderate (-)	Low (+/-)	Very low (+/nil)	Moderate (-)	Very high (-)	Very high 🟩 🟦
Seagrasses								
B1/A2 2035	Moderate (-)	Moderate (-)	Moderate (-)	Low (+/nil)	Very low (+)	Moderate (-)	Low (-)	Moderate 🟩 🟦
B1 2100	Moderate (-)	Moderate (-)	Moderate (-)	Low (+/nil)	Very low (+)	Moderate (-)	Moderate (-)	Moderate 🟩 🟦
A2 2100	High (-)	High (-)	High (-)	Moderate (+/-)	Very low (+)	High (-)	Moderate (-)	High 🟩 🟦



The effects of sea-level rise are expected to result in losses of around 10% of mangrove habitat in most PICTs where mangroves are common today by 2035 for the B1 and A2 emissions scenarios (**Table 6.5**). By 2100, losses are expected to be around 50% for the B1 scenario and 60% for the A2 scenario in most of these PICTs, with losses of up to 80% possible in some PICTs (e.g. Tonga).

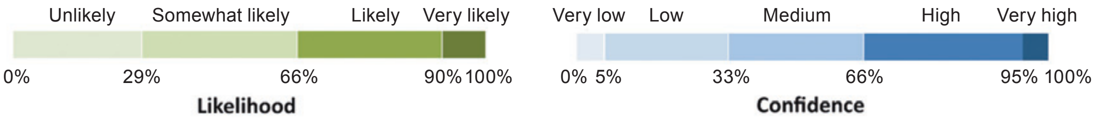
6.7.2 Seagrasses

On balance, the combined changes to the key attributes of the environment for seagrasses are expected to cause moderate losses of these important fish habitats (**Table 6.4**). In intertidal and shallow-water habitats, the projected increases in air temperature, SST, sediment deposition, turbidity, storm surge and algal overgrowth from elevated nutrient loads, and decreases in light and salinity from higher runoff are expected to interact to create more hostile environments for many seagrass species. Seagrasses growing in estuaries, and in fringing reef and bay or lagoon habitats adjacent to high islands heavily exposed to increased runoff, are likely to be more vulnerable than those growing on atolls or on barrier and patch reefs (Section 6.2.2). Although deepwater seagrasses will be relatively protected from disturbances caused by stronger waves, reductions in light will affect their survival and productivity.

Sea-level rise is expected to result in the loss of those seagrasses growing in deep water at their present depth limit. Although there will be opportunities for seagrass to expand landward in some places, physical barriers or unsuitable substrate will prevent colonisation in other areas.

Table 6.5 Projected percentage loss in areas of mangrove and seagrass habitats for the B1 and A2 emissions scenarios in 2035 and 2100 in Pacific Island countries and territories (PICTs) that have total areas of mangroves and seagrasses > 5 km^2. These estimates are based on the expert opinion of the authors because data on the land area to be inundated for the B1 and A2 scenarios are not yet available to inform a quantitative assessment. The estimates include the perceived scope for the major areas of the existing mangroves and seagrasses in each PICT to migrate, or not migrate, landwards as the case may be.

PICT	Mangroves				Seagrasses			
	B1/A2 2035	B1 2100	A2 2100		B1/A2 2035	B1 2100	A2 2100	
Melanesia								
Fiji	10	50	60	🟩 🟦	< 5	5–10	10–20	🟩 🟦
New Caledonia	10	50	60	🟩 🟦	5–10	5–20	10–25	🟩 🟦
PNG	10	50	60	🟩 🟦	5–20	5–30	10–35	🟩 🟦
Solomon Islands	10	50	60	🟩 🟦	5–20	5–30	10–35	🟩 🟦
Vanuatu	10	50	60	🟩 🟦	5–20	5–30	10–35	🟩 🟦
Micronesia								
FSM	10	50	60	🟩 🟦	< 5–10	5–25	10–30	🟩 🟦
Guam	10	60	70	▧ ▢	5–20	5–35	10–50	🟩 🟦
CNMI	30	70	80	▧ ▢	< 5–10	5–25	10–35	🟩 🟦
Palau	10	50	60	🟩 🟦	< 5–10	5–25	10–35	🟩 🟦
Polynesia								
French Polynesia	10	50	60	🟩 🟦	< 5	5–10	10–20	🟩 🟦
Samoa	10	50	60	🟩 🟦	5–20	5–35	10–50	🟩 ▢
Tonga	30	70	80	▧ ▢	5–10	5–20	10–20	🟩 ▢



When the effects of changes to all the various features of the environment are combined, seagrass habitats are expected to have moderate vulnerability to climate change for the B1 and A2 emissions scenarios in 2035 and the B1 scenario in 2100, increasing to a high vulnerability under the A2 scenario in 2100 (Table 6.4).

Based on a simple application of observed impacts from such synergistic effects in present-day seagrass habitats, future losses of seagrasses in the tropical Pacific could be in the range of 5–20% by 2035 for the B1 and A2 emissions scenarios. By 2100, the losses could be as great as 5–30% for B1 and 10–35% for A2 (Table 6.5). Seagrass losses are not expected to be as great in subtropical areas because the projected decreases in rainfall (Chapter 2) are likely to limit impacts. Nevertheless, reductions in seagrass habitat of 5–10% may occur in these parts of the region for the B1 and A2 scenarios in 2035, increasing to potential losses of 5–20% for B1 and 10–25% for A2 in 2100.

6.7.3 Intertidal flats

The intertidal flat habitats of the region are expected to be primarily vulnerable to sea-level rise, so that any conclusions about the integrated effects of climate change are essentially the same as those presented in Section 6.6.3. As sea level rises, it is highly likely that intertidal flats will be lost around many high islands due to steep terrain or infrastructure barriers. There will also be limits on the landward progression of intertidal lagoonal habitats on atolls with narrow land areas.

Intertidal flats are expected to have low to moderate vulnerability to climate change for the B1 and A2 emissions scenarios in 2035, increasing to high for the B1 and A2 scenarios in 2100. Projections are being developed based on currently available topographic mapping to estimate the percentage loss of intertidal sand and mud flats from the expected rises in sea level for the B1 and A2 emissions scenarios in 2035 and 2100.

6.8 Uncertainty, gaps in knowledge and future research

There are still major gaps in knowledge of the distribution, diversity and coverage of mangrove and seagrass habitats, and the areas of intertidal flats, across the tropical Pacific. Indeed, caution is needed in interpreting the information on coastal fish habitats presented here because much of it is outdated, or based on limited surveys. In many cases, the areas of mangroves, seagrasses and intertidal flats are likely to be (often gross) underestimates. The best estimates are for mangroves and seagrasses in New Caledonia due to the extensive research efforts there. Reasonable estimates are also available for mangroves in some other PICTs, such as FSM, American Samoa, Tonga, and Wallis and Futuna, despite the fact that assessing changes in mangrove area over time in the tropical Pacific is difficult[253].

Systematic mapping of mangroves, seagrasses and intertidal flats for all PICTs, including habitat area, plant density and species composition, is a research priority. In the case of seagrass habitats, mapping is also needed to show the depths to which existing meadows extend. This information will (1) raise awareness among coastal planners about the locations and scale of these important fisheries habitats; and (2) provide a baseline for monitoring changes in the area, density and species composition of mangroves and seagrasses, and the area of intertidal flats.

The species composition and relative abundance of mangroves and seagrasses are relatively well known in most PICTs (**Table 6.1**), but this is not the case for the epifauna and infauna associated with these habitats. Faunal studies are needed at a basic level, followed by comparisons of biodiversity, relative abundance and size composition of fauna among mangroves, seagrasses and intertidal flats, and between different mosaics of these habitats. Movements of animals among these habitats and between them and coral reefs, in terms of life history development and foraging behaviour described for other parts of the world[7–9,12], remain poorly understood in the tropical Pacific. Such research will greatly improve our understanding of food webs and the other ecosystem services provided by mangroves, seagrasses and intertidal flats to coastal fisheries. It will also allow knowledge to progress from the limited range of examples of habitat roles to an understanding of the processes underpinning these roles.

More reliable data on sea-level rise and sedimentation rates are needed throughout the region to enable more accurate predictions of the responses of mangroves and intertidal flats and the possible mitigating effects of sedimentation[254]. Reliable data on sea-level rise are now being collected in many PICTs with instrumentation installed through the South Pacific Sea Level and Climate Monitoring Project (Australian Bureau of Meteorology[iii]). However, the time-series is not long enough to elucidate a trend and recordings must continue for many years. Caution will also be needed in interpreting these data for the reasons outlined in Chapter 3, and because the tectonics of coastlines within PICTs vary[215]. It will also be important to improve the resolution of topographic maps so that the areas projected to be inundated, which may be suitable for colonisation by mangroves and seagrasses, can be estimated more accurately and protected.

Even with a concerted effort to address the large gaps in knowledge outlined above, it will be difficult to separate the effects of climate change on coastal habitats from other natural and human impacts. Despite the need to understand the potential effects of climate change, it is imperative that existing research on the effects of changes to catchments and shorelines on these habitats continues to receive the necessary funding. The possible impacts from agriculture, forestry and mining, for example, are likely to be much greater than those from climate change in the short to medium term. Understanding the processes behind such impacts, and the most appropriate measures to ameliorate the adverse effects, is also likely to build the resilience of coastal fish habitats to climate change. Ideally, monitoring programmes should be designed that enable managers to separate the effects of climate change from local stressors. Managers can then identify adaptations needed to maintain the habitat mosaic in the face of climate change[5,217,255], and assess the effectiveness of these adaptations.

The need to downscale global climate models to provide more accurate assessments of projected changes in surface climate and features of the tropical Pacific Ocean at scales more relevant to PICTs is also important for integrated coastal zone management in

[iii] www.bom.gov.au/pacificsealevel

PICTs[iv] (Chapters 2 and 3). When combined with the results of the research outlined above, this information will enable managers to identify (1) the mangrove areas and seagrass meadows most at risk from local impacts, e.g. higher levels of runoff; and (2) the locations where management effort should be focused.

The substantial research list described above is beyond the capacity of most PICTs. Many will need to form partnerships with scientific institutions within and outside the region, and seek the assistance of the communities who live adjacent to these habitats, to fill the gaps. Location-specific studies at representative sites across the region are especially needed, because most of the present knowledge and assessments are extrapolated from other parts of the world. The Seagrass-Watch[v] programme offers a model for providing useful and spatially extensive environmental monitoring data for some of the necessary surveys in PICTs where resources are limited.

6.9 Management implications and recommendations

The high level of connectivity among coral reefs, mangroves, seagrasses and intertidal flats (the coastal habitat mosaic) means that the loss of one habitat could have implications for the other components of the mosaic. Therefore, an over-riding priority for management should be to secure connectivity among all these habitats to enhance the resilience of coastal ecosystems[7] and help safeguard coastal fisheries production[6] in the face of future climate change (Chapter 9). The practical management measures for maintaining this mosaic are summarised below.

- Improve integrated coastal zone management to reduce existing impacts on mangroves, seagrasses and intertidal flats from agriculture, forestry, mining and road construction in catchments, and sand mining and construction on the coast. These measures will help maximise the natural potential of these habitats to adapt, and will be particularly important in reducing the synergistic effects of terrestrial pollution and climate change on coastal habitats[2,21,256–259].
- Strengthen governance and legislation to ensure the sustainable use and protection of vegetated coastal habitats[29]. There is a continuing need to build the capacity of management agencies to improve (1) the ability of staff to understand the threats to coastal fish habitats; (2) the networks for transferring this knowledge to communities through co-management or community-based management arrangements; (3) the national regulations needed to underpin effective protection for mangroves and seagrasses; and (4) local and national systems to achieve compliance with regulations.

[iv] This work is now being done progressively for the tropical Pacific by the Australian Bureau of Meteorology and CSIRO, and partners, under the Pacific Climate Change Science Programme; see www.cawcr.gov.au/projects/PCCSP

[v] www.seagrasswatch.org/about.html

- Implement and facilitate interventions that are likely to support coastal fish habitats to adapt to climate change. For example, plan to allow for landward migration of mangroves, seagrasses and intertidal flats where possible. This will involve placing infrastructure on higher ground and removing existing barriers in low-lying areas.
- Initiate regular high-level discussions between planners and fisheries managers to ensure that barriers to adaptation of coastal fisheries habitats are minimised as plans are developed to assist all sectors respond to climate change.
- Engage local communities in sustainable management of coastal habitats, such as supporting community-based conservation areas where local committees manage or restrict use of areas based on the state of resources[29]. This requires regular transfer of research and monitoring information to communities to build local capacity.
- Promote community-based co-management approaches, where management is carried out primarily by local stakeholders in close cooperation with relevant local and national government institutions and non-government organisations. Adaptive co-management makes optimum use of social capital, such as existing (or assigned) resource rights, local governance, traditional knowledge, self-interest and self-enforcement capacity. It is increasingly seen as an effective way to implement conservation and management measures where customary tenure exists, e.g. throughout much of Melanesia.

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