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Chapter 9

Vulnerability of coastal fisheries in the tropical Pacific to climate change

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> *'Reef fish fisheries have long sustained coastal communities throughout the tropics as an important, sometimes sole, source of protein and livelihood.'* (Sadovy 2005)[i]

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[i] Sadovy Y (2005) Trouble on the reef: The imperative for managing vulnerable and valuable fisheries. *Fish and Fisheries* 6, 167–185.

Contents

9.1 Introduction

Although the coastal fisheries of the Pacific Island countries and territories (PICTs) differ considerably from the industrial tuna fisheries of the region (Chapter 8), the importance of coastal fisheries cannot be overstated. Throughout the tropical Pacific, coastal fisheries contribute significantly to the food security, livelihoods, and culture of both rural communities and urban populations[1–5]. In the majority of PICTs, fish consumption by coastal communities exceeds 50 kg per person per year, and is > 90 kg per person per year in six PICTs[4]. In comparison, average global fish consumption per person is 16–18 kg per year[6,7].

Not surprisingly, therefore, coastal fisheries in the tropical Pacific are based mainly on subsistence activities to provide fish and invertebrates for household food[1,4,8,9]. Nevertheless, an average of 47% of households in fishing communities also earn their first or second income from selling surplus fish and invertebrates caught from coastal and nearshore waters[10]. Specialised fisheries for coastal invertebrates (e.g. sea cucumbers and trochus) and fish (e.g. groupers and snappers) for export commodities, have also contributed substantially to national income and local livelihoods over the years. The only parts of the tropical Pacific where coastal fisheries do not help underpin food security and livelihoods are the inland areas of Papua New Guinea (PNG), Solomon Islands and Fiji (Chapter 10). The significance of coastal fisheries is demonstrated by the total contributions of subsistence and commercial catches to gross domestic product (GDP) across the region; together, they are estimated to be worth USD 272 million. This is considerably higher than the USD 200 million derived from locally-based industrial tuna fleets[5].

The benefits of coastal fisheries depend on the coral reefs, mangroves, seagrasses and intertidal sand and mud flats that support the many fish and invertebrate species harvested. Taken together, these habitats constitute the littoral and sublittoral areas surrounding PICTs (Chapters 5 and 6), and provide shelter and/or feeding areas for various life history stages of the hundreds of species of fish and invertebrates caught regularly by coastal communities in the tropical Pacific[1,10].

In some areas, the benefits to PICTs from coastal fisheries have been undermined by habitat degradation or loss, resulting from coastal development, pollution, sedimentation from careless land use within catchments, reclamation or excavation of reef areas, and destructive fishing practices[11–14], as well as over-exploitation of coastal fish and invertebrates[8,15–17]. In coral reef habitats, the increasing range of anthropogenic effects is compounding the disturbances caused by natural events, such as cyclones and outbreaks of the coral feeding crown-of-thorns starfish *Acanthaster planci*[18–19]. Crown-of-thorns starfish, for example, have contributed greatly to loss of coral in Fiji and French Polynesia over the last 40 years and remain the major cause of reef degradation in much of the Pacific[20–21]. Together with reduction of seagrass and mangrove habitats (Chapter 6), damage to complex coral reef ecosystems significantly reduces biological productivity in tropical coastal waters[22].

Overfishing in the tropical Pacific has been driven mainly by rapid growth of human populations (Chapter 1), the need for coastal communities to earn cash in increasingly 'Westernised' societies, greater demand for export commodities, and a lack of alternative livelihoods[2,23–25]. Exploitation of fisheries resources is strongly linked to economic development at the national level, and availability of alternative income opportunities at the community level[9,26]. Coastal communities with limited access to alternative livelihoods are most vulnerable because of their high dependence on coastal fisheries resources. This dependence is demonstrated by the direct relationship between small-scale artisanal invertebrate catches and daily cash expenditure[26].

Projected changes to the surface climate of the region and the tropical Pacific Ocean (Chapters 2 and 3) have the potential to affect the productivity of coastal fisheries, and the success of management measures to improve sustainability of these essential resources. Recent and rapid changes in the global climate (Chapter 2) are having major impacts on physical and biological processes across a wide range of ecosystems[27–29]. Periodic large-scale climatic events, such as the El Niño-Southern Oscillation, are known to have significant effects on the distribution or productivity of exploited fish populations[30–33], leading to widespread concern about the future impact of global climate change[34] (Chapters 1 and 8). Variations in water temperature, current regimes, availability of nutrients and the pH of the ocean can be expected to have a direct influence on the physiology, growth and replenishment of many fisheries species, leading to marked changes in their size, abundance and/or distribution[35–37]. Changes to water temperature, ocean acidity, severity of storms and cyclones, sea level, sedimentation, and rainfall are also likely to affect coastal fisheries indirectly by altering the extent and structure of the coral reefs, mangroves, seagrasses and intertidal areas that support them (Chapters 5 and 6).

The purpose of this chapter is to assess the vulnerability of coastal fisheries in the tropical Pacific to projected climate change. As a prelude to this assessment, we summarise the nature and status of coastal fisheries by describing the main species of fish and invertebrates harvested, together with their uses, recent catch levels, status and estimated sustainable production. We then use the vulnerability framework outlined in Chapter 1 to assess (1) the exposure and sensitivity of the major groups of fish and invertebrates to projected changes in surface climate (Chapter 2), oceanic conditions (Chapter 3) and the habitats that support them (Chapters 5 and 6); and (2) the adaptive capacity of these species to reduce the potential impact stemming from their exposure and sensitivities. Changes in fisheries production by 2035 and 2100 are projected for representative low (B1) and high emissions (A2) scenarios[38] (Chapter 1).

We conclude with the gaps in knowledge that currently limit confidence in vulnerability assessments for coastal fisheries, the research needed to fill these gaps, and the management actions required to reduce the vulnerability of coastal fisheries in the tropical Pacific to climate change.

9.2 Nature and status of coastal fisheries

9.2.1 Main fisheries and their uses

For the purposes of this chapter, coastal fisheries are defined as the harvesting of wild demersal fish and invertebrates from inshore coastal habitats to a depth of 50 m, as well as pelagic fish caught in nearshore waters within 10 km of the coast. We give only limited consideration to finfish and invertebrates that spend either part or all of their lives in brackish water because these species are covered in Chapter 10. Marine and estuarine ecosystems are, however, strongly interconnected and it is difficult to attribute some fisheries activities (e.g. trawl-based fisheries for penaeid shrimp in PNG) to a single ecosystem.

We do not consider the deep slope fisheries for snappers, groupers and other species[1] because these deeper-water environments are likely to be buffered against the main effects of climate change, particularly increasing temperature, during the timeframes (25–90 years) considered in this chapter. Deepwater fish species may be affected by changes in productivity and food supply due to changes in current patterns and eddies (Chapter 3). Information on the biology of these fish is very limited, however, preventing effective assessment of their vulnerability to climate change.

This assessment does not include sharks, rays, reptiles or mammals. The effects of climate change on sharks and rays are generally unknown but assumed to be similar to those for finfish occupying equivalent habitat types. For example, reef sharks such as *Carcharhinus amblyrhynchos* and *Triaenodon obesus* are highly dependent on coral reefs and are likely to be affected negatively by extensive habitat degradation[39]. Although turtles, crocodiles, dolphins and dugongs are culturally important and clearly vulnerable to climate change[40], they are not assessed here. With some exceptions[41], these species generally make a limited contribution to subsistence or commercial fisheries in PICTs and are increasingly subject to environmental protection or regulations based on customary use.

The coastal fisheries of the tropical Pacific, as we define them, are based on wild capture of a wide range of fish and invertebrate species and are best thought of as low-investment, small-scale, multi-gear, multi-species fisheries. Even so, there are marked differences in catch composition among PICTs[1,10]. In particular, the number of species caught declines from west to east, corresponding with known gradients in the biodiversity of marine species[42] (Chapter 1). Further differences in catch composition arise from the use of different fishing methods, variation in available fish habitats (Chapters 5 and 6), and regional differences in dietary preferences and cultural practices of Pacific Island people[1].

Considering both target species and their key supporting habitats, the coastal fisheries of the region fall into four distinct categories (1) demersal (bottom-dwelling) fish; (2) nearshore pelagic fish; (3) targeted commercial invertebrates; and (4) shallow subtidal and intertidal invertebrates. Importantly, these four categories of fisheries may be affected in different ways by climate change.

The main species caught by these fisheries, the habitats that support them, the main fishing methods, and the uses of the resources (subsistence and income generation) are summarised below. This review of the main groups of fish and invertebrates comprising coastal fisheries, and the present range of coastal fishing activities, is based largely on comprehensive sampling conducted by the Pacific Regional Oceanic and Coastal Fisheries (PROCFish) Development Project, implemented by the Secretariat of the Pacific Community (SPC)[10] (Appendix 9.1).

9.2.1.1 Demersal fish

A diverse range of demersal fish are caught from the coastal waters of PICTs, spanning specialist species associated mainly with coral reefs to generalist species that occur across a range of different habitats (**Figure 9.1**). The greatest abundance and diversity of fish are caught around coral habitats[1,9,10,17]. However, fishing also occurs close to mangroves, in seagrass meadows and over inter-reefal habitats with little biological structure (Chapters 6 and 10).

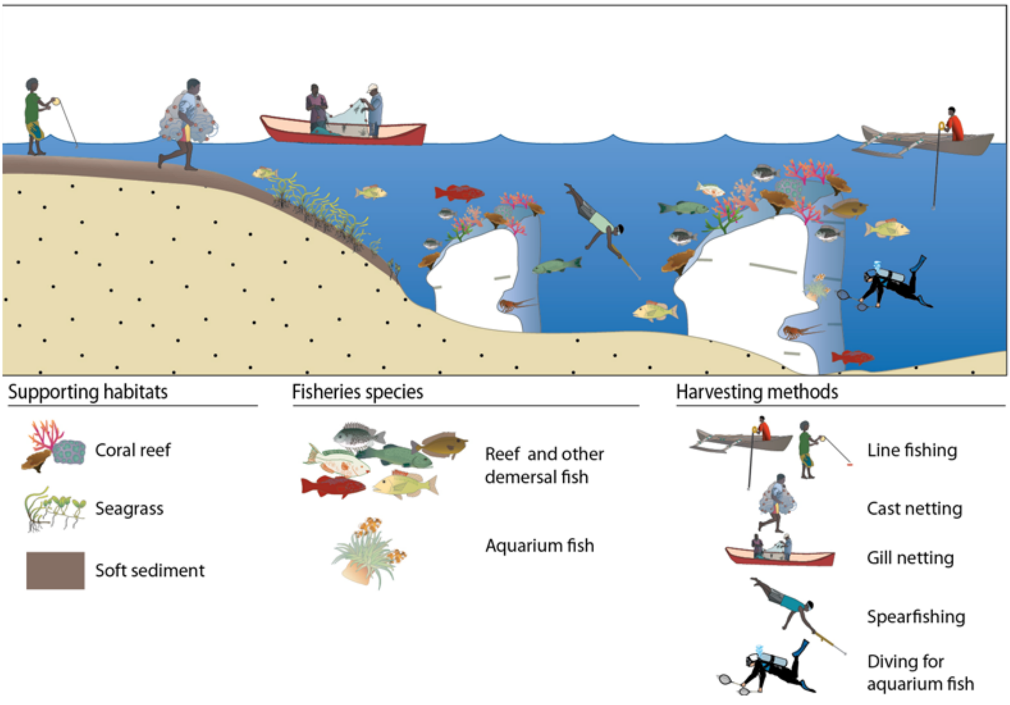


Figure 9.1 Main habitats where demersal fish are caught in the tropical Pacific, and the most common methods used to catch these fish.

The main families of demersal coral reef fish caught for subsistence and livelihoods are fairly consistent across the tropical Pacific (**Figure 9.2**, **Table 9.1**), i.e. catches are dominated by carnivorous emperors (Lethrinidae), snappers (Lutjanidae) and groupers (Serranidae), as well as herbivorous parrotfish (Scaridae), surgeonfish (Acanthuridae) and rabbitfish (Siganidae). In Melanesia, catches of demersal fish are comprised mainly of emperors, whereas the composition of catches in Micronesia and Polynesia varies depending on the country or territory (**Table 9.1**). Across these two regions, carnivorous species dominated catches in Kiribati, Marshall Islands, Palau, Niue and Tonga, whereas herbivorous surgeonfish, parrotfish, rabbitfish, or drummers (Kyphosidae) were caught more often in Federated States of Micronesia (FSM), Nauru, Cook Islands, French Polynesia and Samoa (**Table 9.1**).

Table 9.1 Proportional catches of major families of demersal fish in 17 Pacific Island countries and territories (PICTs). Information based on extrapolated catches from socio-economic surveys conducted in 4–5 coastal fishing communities in each PICT between 2002 and 2008. The trophic group of each family is designated as carnivore (C) or herbivore (H), based on the predominant role of species in each family (source: SPC PROCFish Project).

PICT	Family (trophic group)											
	Lethrinidae (C)	Acanthuridae (H)	Scaridae (H)	Serranidae (C)	Lutjanidae (C)	Siganidae (H)	Holocentridae (C)	Mullidae (C)	Kyphosidae (H)	Labridae (C)	Balistidae (C)	Others* (C + H)
Melanesia	**20.4**	**7.2**	**8.4**	**8.5**	**8.9**	**6.4**	**1.3**	**3.6**	**1.2**	**0.9**	**2.4**	**30.7**
Fiji	37.4	7.7	2.8	9.4	8.0	1.4	1.8	2.1	0.0	0.0	1.8	27.6
New Caledonia	21.5	10.7	11.5	12.7	3.1	10.3	0.0	4.4	0.0	0.1	0.0	26.0
PNG	14.5	1.9	5.8	5.2	16.0	4.2	0.7	2.1	1.8	0.7	2.1	44.9
Solomon Islands	10.5	5.5	9.2	13.1	18.1	2.0	3.3	1.8	0.1	3.9	4.0	28.5
Vanuatu	17.8	9.0	12.1	1.3	0.9	13.3	1.2	7.6	4.4	0.0	4.5	27.8
Micronesia	**12.8**	**14.0**	**11.4**	**14.3**	**10.9**	**9.1**	**2.1**	**3.1**	**1.7**	**0.7**	**0.3**	**19.7**
FSM	7.8	29.3	26.4	8.1	1.2	14.0	0.1	2.9	0.0	1.0	0.0	9.2
Kiribati	9.2	2.5	2.0	10.8	11.0	0.4	2.0	3.6	0.3	1.0	0.1	57.2
Marshall Islands	10.5	9.5	4.5	28.8	17.2	12.2	3.0	3.7	5.6	0.2	0.3	4.6
Nauru	0.0	34.1	8.3	6.6	10.4	0.0	10.9	0.0	4.5	0.0	4.0	21.2
Palau	26.8	9.5	13.5	11.4	14.4	12.1	0.9	3.1	0.4	0.6	0.1	7.1
Polynesia	**13.2**	**16.8**	**15.4**	**8.4**	**7.2**	**3.1**	**6.1**	**2.8**	**5.7**	**1.3**	**0.2**	**19.8**
Cook Islands	2.6	10.4	36.8	9.7	2.3	4.6	4.9	4.1	14.5	2.3	0.0	7.9
French Polynesia	4.6	19.4	18.1	9.4	4.3	3.3	10.0	4.0	2.0	1.0	0.0	23.8
Niue	0.3	2.4	2.2	6.4	1.3	0.0	22.3	1.2	25.0	4.7	0.3	34.0
Samoa	13.6	22.9	18.7	5.0	5.4	5.1	8.1	3.7	0.7	1.9	0.8	14.0
Tonga	40.3	12.9	11.0	10.9	9.4	4.7	0.8	1.4	1.5	1.3	0.2	5.5
Tuvalu	9.4	17.4	3.1	10.9	14.7	0.8	4.1	0.8	8.7	0.1	0.0	29.9
Wallis and Futuna	14.5	21.8	4.9	3.7	9.7	0.0	3.1	2.7	2.0	0.0	0.1	37.6

* Includes a wide range of species, such as trevallies (Carangidae) and mullet (Mugilidae).

Regional differences in catch composition do not reflect the availability of fish. Rather, comparisons of the relative importance of the main fish families in catches, with estimates of their average biomass from underwater visual census, show that emperors, groupers, parrotfish and surgeonfish are differentially selected among PICTs (**Figure 9.2**, **Table 9.2**). This selection is presumably due to regional variation in fishing techniques, and preferences for different fish as food.

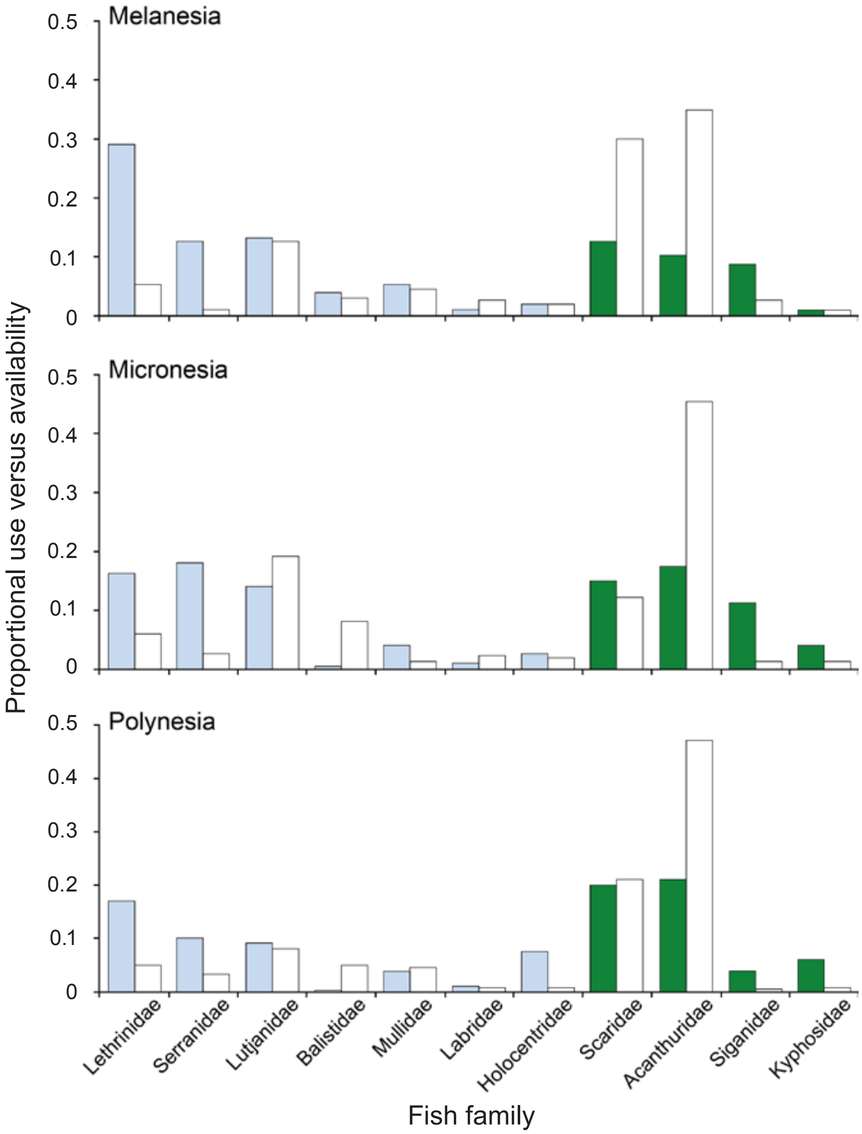


Figure 9.2 Proportional use versus availability of the 11 most harvested families of demersal fish. Proportional use (solid column) was estimated from extrapolated catches from socio-economic surveys conducted in 4–5 coastal fishing communities within each Pacific Island country and territory (PICT) between 2002 and 2008. Availability of each family (blank column) was assessed based on average biomass (tonnes per km^2) estimated using visual census at 1–4 coral reef habitats at 4–5 sites within each of 17 PICTs, between 2002 and 2008. The primary trophic group of each family is designated as carnivore (blue) or herbivore (green) (source: SPC PROCFish Project).

The fishing methods used to catch demersal fish in the tropical Pacific are diverse (**Figure 9.1**). They include handlines, gill nets, spearguns and handheld spears, cast and scoop nets, and mobile and permanent artisanal and commercial fish traps. The traps are made from stones, sticks and/or wire mesh and concentrate fish as they retreat from shallow habitats during tidal exposure, or pass through passages to atoll lagoons. Traditionally, fish are also chased into 'drive-in' nets and corrals[1]. Handlines are used more frequently in Melanesia, than in Micronesia and Polynesia, whereas handspears, spearguns and gill nets are widespread[43]. The fishing method influences the range of species caught[44], as well as the impact of fishing on the habitat. Highly destructive fishing practices (e.g. dynamite, derris root and cyanide) rapidly deplete both target and non-target species, and also contribute to habitat degradation, further increasing the likelihood of overfishing.

Table 9.2 Average biomass (tonnes per km^2) of commonly harvested demersal fish families associated with coral reef habitats. Information derived from underwater visual census at 1–4 coral reef habitats at 4–5 sites within each of 17 Pacific Island countries and territories (PICTs) between 2002 and 2008. The trophic group of each family is designated as carnivore (C) or herbivore (H), based on the predominant role of species within each family (source: SPC PROCFish Project).

PICT	Family (trophic group)										
	Acanthuridae (H)	Scaridae (H)	Lutjanidae (C)	Lethrinidae (C)	Balistidae (C)	Mullidae (C)	Serranidae (C)	Labridae (C)	Holocentridae (C)	Siganidae (H)	Kyphosidae (H)
Melanesia	**40.9**	**35.0**	**15.0**	**6.6**	**2.9**	**4.5**	**2.3**	**3.0**	**2.2**	**3.5**	**1.3**
Fiji	27.2	30.6	10.2	4.4	1.1	3.2	1.4	3.5	0.7	4.8	0.2
New Caledonia	26.3	41.3	3.3	3.1	0.3	3.8	2.4	2.1	0.4	3.4	0.1
PNG	54.5	29.3	20.2	6.5	2.8	4.1	1.9	2.5	3.6	1.9	1.9
Solomon Islands	44.7	22.4	21.8	13.1	7.5	7.9	3.2	2.8	4.0	4.3	0.2
Vanuatu	51.8	51.7	19.4	5.8	2.7	3.4	2.8	4.3	2.1	3.2	4.3
Micronesia	**62.3**	**16.6**	**25.7**	**8.9**	**12.5**	**2.1**	**4.1**	**3.4**	**2.0**	**0.9**	**1.3**
FSM	28.3	25.9	10.2	9.1	1.7	1.6	0.7	1.3	1.7	0.8	1.3
Kiribati	72.9	18.5	88.4	18.4	24.2	2.7	12.6	12.2	2.7	0.2	3.6
Marshall Islands	22.0	17.3	10.8	8.4	1.3	3.3	3.8	0.9	2.0	1.1	0.0
Nauru	153.4	6.9	4.3	4.5	34.2	0.2	2.1	0.1	1.5	0.1	21.2
Palau	34.8	14.5	14.6	4.2	1.2	2.9	1.3	2.3	2.2	2.2	0.4
Polynesia	**40.4**	**17.8**	**7.3**	**4.8**	**3.9**	**3.6**	**2.7**	**1.5**	**1.1**	**0.8**	**1.6**
Cook Islands	59.3	13.8	1.2	3.0	1.7	12.3	3.9	1.8	0.6	0.3	0.7
French Polynesia	23.2	25.4	2.7	4.7	5.4	4.0	1.7	1.2	0.5	0.7	0.0
Niue	35.0	11.2	1.6	0.8	3.5	1.5	2.2	0.8	0.3	0.0	2.4
Samoa	43.7	24.3	7.8	3.0	4.6	2.4	0.8	1.0	1.4	1.2	0.3
Tonga	12.3	8.6	0.9	0.7	0.2	1.7	0.6	1.3	1.0	0.5	0.0
Tuvalu	77.7	32.4	26.7	14.6	10.7	0.8	7.7	3.6	1.3	1.6	6.8
Wallis and Futuna	31.8	8.8	10.5	6.8	1.4	2.2	1.8	0.9	2.8	0.5	0.7

In all but the most remote locations, demersal fish contribute to both food security (subsistence) and livelihoods (to earn income through sales at markets) in rural and urban areas. In general, however, catches for subsistence far exceed those made for sale, often by several-fold[5,45] (Section 9.2.2). Small-scale commercial (artisanal) fisheries for demersal fish are most important in PICTs where urban populations are large relative to the total population (e.g. Fiji, French Polynesia, Kiribati, New Caledonia and Tonga), or where the large urban areas or national or provincial capitals allow for market opportunities (e.g. PNG and Solomon Islands). In these PICTs, demersal fish are caught across a wide range of locations, including increasingly remote and outlying areas, to supply central markets[46].

Other ways in which coastal demersal fish have been used to earn income are through the capture of fish for the live fish food trade and the market for tropical marine ornamental products[47,48]. Several species of groupers, and the large wrasse, *Cheilinus undulatus* (Labridae), have been caught in some countries in the western Pacific to supply the export trade in live food fish. It is estimated that as much as 30,000 tonnes of live reef fish are caught per year within the Asia-Pacific region to supply this trade[49], although official figures are 13,000–14,000 tonnes per year, with an annual value of USD 350 million[50]. These highly valuable species are targeted by specialised operations[5,51]. However, catches from the Pacific have usually comprised < 10% of the trade and have recently ceased due to environmental concerns, and ciguatera poisoning from fish caught in Kiribati.

Smaller species associated with coral reefs, such as damselfish (Pomacentridae), butterflyfish (Chaetodontidae), wrasses (Labridae), triggerfish (Balistidae), cardinalfish (Apogonidae) and gobies (Gobiidae) are caught for export to the ornamental (aquarium) market in the United States, Asia and Europe[48,52–54]. This trade is estimated to be worth at least USD 300 million per year worldwide[55,56], and makes an important contribution to the national economies of several PICTs. For example, > 600 people are employed in the marine aquarium trade in Fiji. In Kiribati, coral reef aquarium fish account for 78% of export earnings. The trade is also significant in Vanuatu, which exports 180,000 aquarium fish each year[10]. Active fisheries for ornamental specimens also exist in Cook Islands, French Polynesia, Marshall Islands, Palau, Solomon Islands and Tonga[10,48].

9.2.1.2 Nearshore pelagic fish

Although the vast majority of the region's rich tuna resources are caught offshore by industrial fleets (Chapter 8), skipjack tuna *Katsuwonus pelamis*, yellowfin tuna *Thunnus albacares* and bigeye tuna *Thunnus obesus*, and a range of other large pelagic fish species, are also caught in nearshore waters (**Figure 9.3**). Together, these fish contribute significantly to coastal fisheries production and are used for both subsistence and earning income through sales to rural and urban markets. The large pelagic species are caught mostly by trolling along reef edges and within several kilometres of the coast. Increasingly, however, they are also being targeted using mid-water fishing techniques, such as vertical longlines, drop-stone and palu-ahi (mid-water handlines) around low-cost, anchored rafts or fish aggregating devices (FADs) deployed close to shore in depths < 1000 m[7,57].

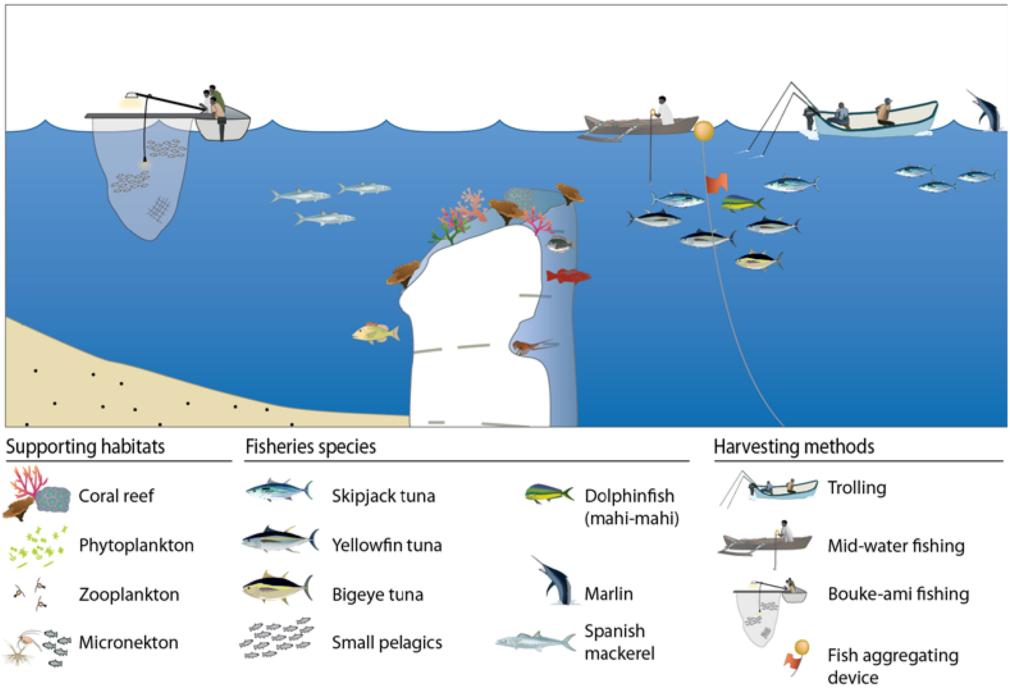


Figure 9.3 Habitats where large and small pelagic fish are caught by the nearshore fishery and the methods used to catch them, including fish aggregating devices (FADs).

Large pelagic fish other than tuna caught by the nearshore fishery include Spanish mackerel *Scomberomorus commerson*, barracuda *Sphyraena* spp., rainbow runner *Elagatis bipinnulata*, wahoo *Acanthocybium solandri*, mahi-mahi *Coryphaena hippurus*, sailfish *Istiophorus platypterus*, marlin *Makaira* spp. and *Tetrapturus* spp.[1]. Spanish mackerel is particularly important in PNG, Solomon Islands, Fiji and New Caledonia, because of the occurrence there of suitable nursery habitats – shallow lagoons fringed with mangroves[1].

Nearshore catches of large pelagic fish can be seasonal, with some of the more sought-after species (e.g. yellowfin tuna and mahi-mahi) caught mainly during cooler months[1]. Accurate information on the relative contribution of tuna and non-tuna species to the nearshore pelagic fishery is not available for many PICTs. This contribution varies among PICTs, however, for example in Niue the non-tuna species comprise more than two thirds of the catch, whereas in Cook Islands two thirds of the landings are tuna[10]. In most PICTs, non-tuna species are currently thought to dominate the nearshore pelagic fishery, because of the fishing methods used.

Small pelagic fish (< 500 g), comprising mackerel (Scombridae), scads (Carangidae), flying fish (Exocoetidae), pilchards and sardines (Clupeidae) and anchovies (Engraulidae), are also caught in nearshore waters throughout the tropical Pacific. They can represent an important part of production for subsistence catches, especially in PICTs with a limited reef area[1], and are one of the resources that could be harvested more widely for food security. Schools of small mackerel *Rastrelliger* spp., bigeye scad *Selar* spp. and mackerel scad *Decapterus* spp. are seasonally abundant and are exploited opportunistically using a combination of seine nets, gill nets, cast nets and scoop nets. Some artisanal fisheries target small pelagics to supply bait for industrial pole-and-line tuna fleets, for example, in Solomon Islands and Fiji[58,59].

In contrast to demersal fish, several species targeted by the nearshore pelagic fishery (tuna, mahi-mahi, wahoo, marlin and small pelagic species) are not highly dependent on coastal habitats. Thus, although these species associate closely with nearshore habitats for feeding and shelter, they are likely to be relatively insensitive to changes in coral cover and composition of coral species.

9.2.1.3 Targeted invertebrates

Fisheries for high-value invertebrates (**Figure 9.4**) have a long history throughout the tropical Pacific[1,60]. In fact, harvesting of sea cucumbers for processing into bêche-de-mer (or trepang) was the first intensive commercial fishery in the region, established in Fiji during the early 1800s[61]. Artisanal fisheries for sea cucumbers have brought considerable benefits to remote communities, and supported export enterprises in PICTs such as PNG, Solomon Islands, New Caledonia and Fiji. These benefits have accrued because the harvesting, processing and storage of sea cucumbers is relatively easy and requires no specialised equipment[62]. Exports of up to 1000 tonnes of bêche-de-mer per year were made from PNG and Fiji during peak production in the late 1980s[63] and have remained significant. For example, exports from PNG alone supplied up to 10% of bêche-de-mer caught from the wild worldwide[64] before PNG's recent moratorium on harvesting of sea cucumbers under a national management plan. When exports of bêche-de-mer are converted to wet weight of sea cucumbers, the fisheries in Fiji, Solomon Islands and New Caledonia have landed between 19% and 32% of the weight of tuna caught by national tuna fleets from their exclusive economic zones (EEZs)[10]. The export value of bêche-de-mer from New Caledonia in 2007 (USD 5.3 million) was twice that of tuna[65].

Sea cucumbers have traditionally been collected from coral reef habitats by gleaning (opportunistic gathering) and snorkelling, but also commonly from seagrass meadows and soft substrata near mangroves. However, in some PICTs, the high value of sea cucumbers has induced fishers to invest in larger boats, SCUBA or hookah diving gear, and drag nets. Use of this equipment exacerbates the current overfishing of these valuable resources[66] (Section 9.2.3).

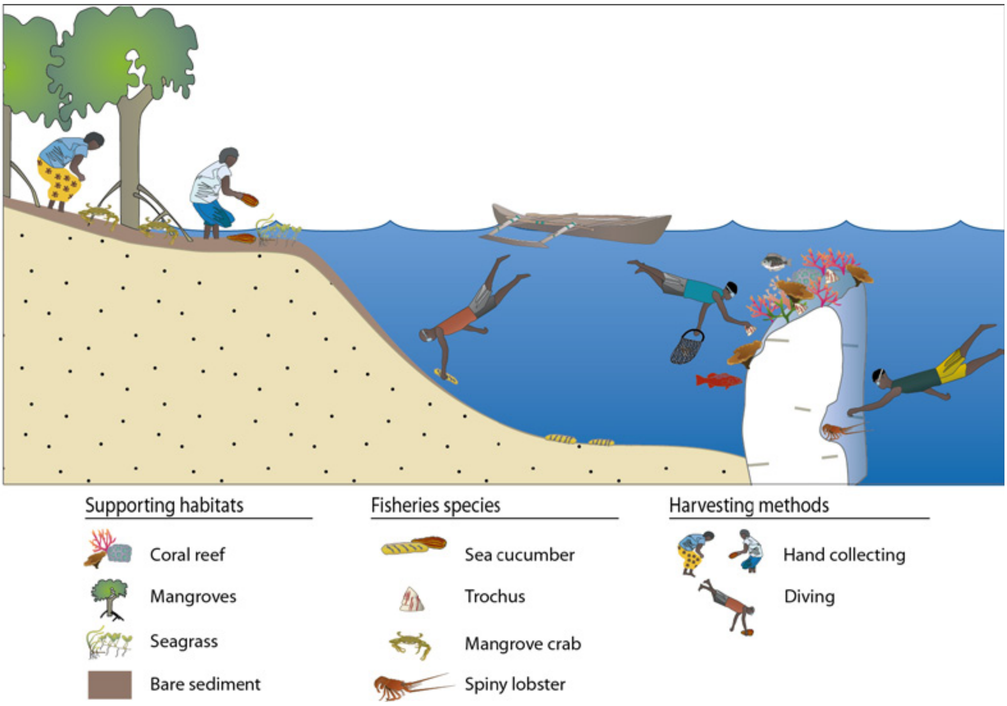


Figure 9.4 Habitats where invertebrates for export and sale to local markets are collected, and the methods used to catch them.

Several species of molluscs are harvested as export commodities in the tropical Pacific. The most important of these is the topshell *Trochus niloticus*, a herbivorous gastropod collected by diving on shallow coral reefs. The nacre of topshell (also known as trochus) has been in demand for buttons since the early 1900s[67], and this species has been extensively introduced beyond its normal geographic range to expand the economic benefits to other PICTs[1,68]. Trochus has contributed substantially to fishery exports for Cook Islands, Fiji, FSM, New Caledonia, PNG, Solomon Islands, Vanuatu and Wallis and Futuna. Over the past century, the combined harvests of topshell from Fiji, PNG and Solomon Islands exceeded 50,000 tonnes, with a present-day value of USD 200 million[10]. Green snail *Turbo marmoratus* has also been harvested and translocated in the tropical Pacific for its nacre, although the quantities involved are low compared with topshell[69]. Before the development of large-scale black pearl farming around 1980 (Chapter 11), ~ 450 tonnes of black-lipped pearl oysters *Pinctada margaritifera* collected from the wild were exported each year from French Polynesia and Cook Islands[70].

Commercial fisheries for crustaceans (spiny lobsters, mangrove crabs and coconut crabs) for sale at local and export markets also occur in many PICTs. Spiny lobsters were caught traditionally by skin divers for local markets, but are now the target of export fisheries in some PICTs, increasing the likelihood of overfishing. Mangrove crabs are caught mainly by being removed from their burrows at low tide, often by women, and are common at central markets in Fiji, FSM, New Caledonia, Palau, PNG, Solomon Islands and Vanuatu. Penaeid shrimp are the basis of a commercial trawl fishery in PNG. Most of the fleet operates in the Gulf of Papua and catches have been as high as 1000 to 1300 tonnes per year, while smaller trawl fisheries have been established at several other locations in PNG[71,72].

9.2.1.4 Shallow subtidal and intertidal invertebrates

Invertebrates inhabiting shallow reeftops and reef platforms, mangrove areas, seagrass meadows, and sand or mud flats exposed or accessible at low tide, are regularly gleaned by people in the tropical Pacific (**Figure 9.5**) (Chapter 6). A large variety of sessile or sedentary invertebrates are harvested in this way (**Table 9.3**). Gleaning is mainly a subsistence activity, although some gastropods are collected for their shells which are made into handicrafts and sold at markets. Several species of sea cucumbers are also collected, processed and sold as bêche-de-mer (see above). Importantly, gleaning is a fall-back fishery for times when adverse weather prevents sea-based fishing activities. The diversity of animals harvested may often be much greater than indicated in **Table 9.3**. For example, at least 50 species of molluscs alone are routinely harvested from shallow coral reefs and mangrove forests in Fiji, Guam, Palau, PNG and Tonga[1].

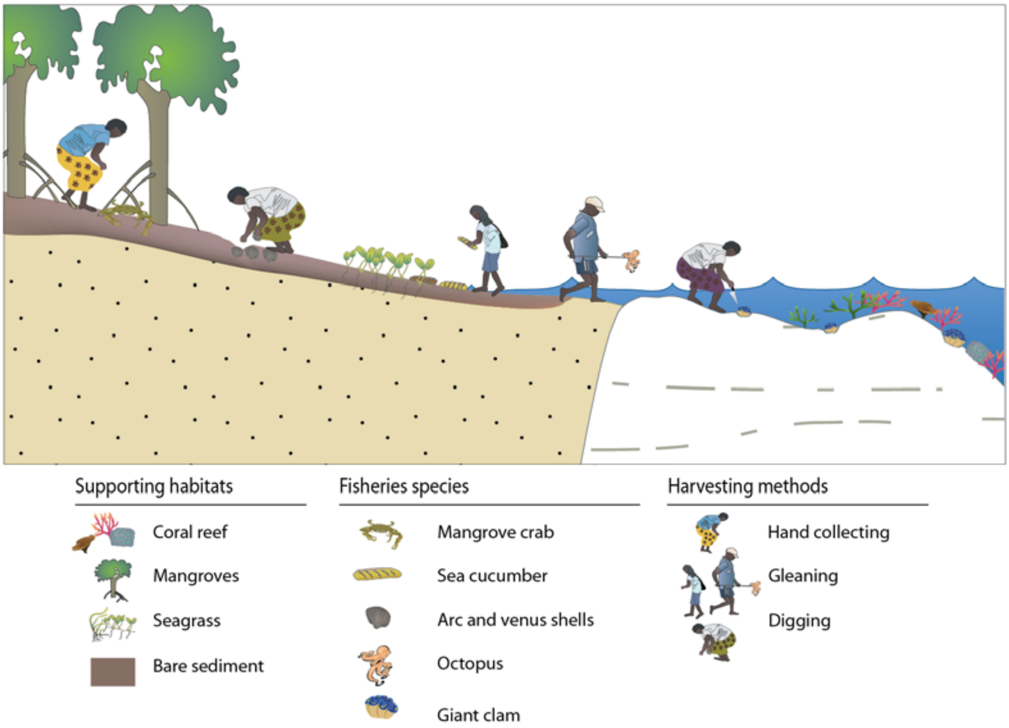


Figure 9.5 Shallow subtidal and intertidal habitats where invertebrates are collected by gleaning, together with a selection of the key species harvested.

Densities of invertebrate species on shallow intertidal reefs and in other coastal habitats can be high (**Table 9.4**). As a result, production from gleaning in subtidal and intertidal areas can be substantial. For example, annual harvests of arc shells *Anadara holoserica* were estimated to be 1800 tonnes for Tarawa Atoll and 3286 tonnes for the Gilbert Islands in the 1980s. Regrettably, potential harvesting of arc shells from Tarawa Lagoon is now threatened by the health risks associated with eating shellfish contaminated by deteriorating water quality, because of dense human populations. In general, harvests of intertidal invertebrates are dominated by bivalves (giant clams, arc and venus shells), echinoderms (sea cucumbers and sea urchins) and gastropods (turban shells, spider shells and trochus) (**Figure 9.6**).

Table 9.3 Average catch composition (percentage wet weight) of the major groups of invertebrates used for food and livelihoods in 17 Pacific Island countries and territories (PICTs). Information based on extrapolated catches from socio-economic surveys conducted in 4–5 coastal fishing communities within each PICT between 2002 and 2008 (source: SPC PROCFish Project).

PICT	Invertebrate groups								
	Giant clams	Sea cucumbers	Gastropods	Spiny lobsters	Crustaceans	Octopus	Bivalves	Trochus	Others
Melanesia									
Fiji	5.1	69.1	2.5	2.6	4.6	4.3	8.3	2.7	0.8
New Caledonia	10.2	5.5	8.1	18.3	28.4	6.5	7.1	15.9	0.0
PNG	13.8	52.1	15.8	3.2	3.6	6.2	4.6	0.8	0.0
Solomon Islands	49.8	0.7	12.7	5.5	12.9	0.8	6.6	9.1	2.0
Vanuatu	5.2	19.9	36.5	0.1	14.0	4.2	18.1	0.8	1.2
Micronesia									
FSM	34.4	13.9	2.1	31.9	3.5	5.9	0.7	7.6	0.0
Kiribati	60.7	3.6	1.5	12.4	2.0	1.1	2.2	0.0	16.5
Marshall Islands	33.4	0.0	39.4	8.7	10.1	7.2	1.2	0.0	0.0
Nauru	0.0	12.3	28.6	10.5	33.5	13.4	0.8	0.7	0.0
Palau	28.5	68.9	0.0	0.7	1.9	0.0	0.0	0.0	0.0
Polynesia									
Cook Islands	30.8	24.4	15.4	15.3	4.3	2.3	2.7	0.8	4.0
French Polynesia	69.1	0.0	3.6	24.1	1.6	0.0	0.1	0.0	1.5
Niue	5.0	3.9	72.1	10.6	5.8	1.2	1.3	0.0	0.0
Samoa	34.4	45.0	2.4	2.1	7.4	3.9	3.1	1.1	0.6
Tonga	24.7	17.4	14.3	8.5	0.0	28.4	0.9	0.0	5.8
Tuvalu	7.5	0.0	46.1	27.5	3.3	2.8	12.7	0.0	0.0
Wallis and Futuna	15.4	1.9	7.7	30.8	9.0	2.2	3.1	29.9	0.0

The species composition and relative abundance of invertebrate catches from coral reefs, and other coastal habitats has been documented across the tropical Pacific (**Table 9.3**), but the total contribution of gleaning to coastal fisheries production for food security is largely unknown. The importance of intertidal gleaning to historical and contemporary seafood consumption is often overlooked, mostly because the entire catch is consumed almost immediately and is highly variable and difficult to characterise. Catches of the larger and more conspicuous invertebrates (e.g. octopus) have often been incorporated in estimates of subsistence reef fisheries[45], but such species may represent only a small percentage of the total fisheries production from gleaning[1] (**Figure 9.6**).

Table 9.4 Mean densities (individuals per ha) of commonly harvested groups of invertebrates caught mainly for export commodities (in light blue), or gleaned from shallow subtidal and intertidal habitats for food security and livelihoods (in darker blue). Information derived from surveys at 4–6 sites in 17 Pacific Island countries and territories (PICTs) between 2002 and 2008 (source: SPC PROCFish Project).

	Invertebrate group														
	Sea cucumbers				**Mother-of-pearl**			**Gastropods**		**Bivalves**				**Others**	
PICT	*Holothuria whitmaei*	*Holothuria scabra*	*Bohadschia argus*	*Holothuria atra*	*Trochus niloticus*	*Pinctada margaritifera*	*Tectus pyramis*	*Turbo* spp.	*Lambis lambis*	*Tridacna maxima*	*Tridacna squamosa*	*Tridacna gigas*	*Anadara* spp. (per m^2)	*Tripneustes gratilla*	*Panulirus* spp.
Melanesia															
Fiji	0.1	72	3.7	174	52	1.8	77	69	8.3	769	8.2	0.0	5.8	16.1	0.2
New Caledonia	5.3	418	22.1	59	252	3.2	226	123	13.5	462	2.8	0.0	1.3	0.2	0.7
PNG	0.8	63	1.8	3	40	2.5	93	18	11.8	244	8.3	0.5	0.1	52.9	1.3
Solomon Islands	0.2	4	1.0	6	20	2.5	141	59	17.1	105	2.9	> 0.1	0.6	0.7	1.5
Vanuatu	1.1	428	5.3	88	188	1.7	23	35	10.3	80	4.0	0.0	2.3	0.5	0.4
Micronesia															
FSM	1.6	0	5.6	70	336	0.9	23	68	8.1	79	0.7	0.0	0.0	> 0.1	0.2
Kiribati	0.2	0	3.5	988	0	3.5	1	0	0.0	5665	1.0	> 0.1	25.8	0.0	0.5
Marshall Islands	0.2	0	2.4	302	16	2.2	3	10	9.3	1024	6.7	0.4	0.0	0.0	0.1
Nauru	0.0	0	0.0	2	0	0.0	0	50	0.0	0	0.0	0.0	0.0	0.0	0.0
Palau	8.4	281	15.7	116	299	2.8	129	32	29.5	240	14.1	0.8	0.0	0.0	0.6
Polynesia															
Cook Islands	0.1	0	0.4	4350	608	0.2	0	1	0.0	635	0.0	0.0	0.0	23.5	0.0
French Polynesia	0.0	0	33.2	1306	1387	2.4	0	35	0.0	5657	0.0	0.0	0.0	0.4	> 0.1
Niue	0.3	0	0.3	0	0	0.0	0	0	0.0	215	0.0	0.0	0.0	0.0	0.0
Samoa	1.1	0	16.2	2231	0	0.0	8	0	0.3	6	< 0.1	0.0	0.0	0.0	0.0
Tonga	3.9	0	19.3	670	195	2.1	65	26	1.3	61	1.0	0.0	0.1	0.5	0.1
Tuvalu	0.7	0	2.7	3	0	0.0	36	3	0.0	78	5.0	0.0	0.0	0.0	> 0.1
Wallis and Futuna	4.3	1.1	17.2	603	91	0.0	15	7	0.0	51	0.0	0.0	0.3	0.0	0.1

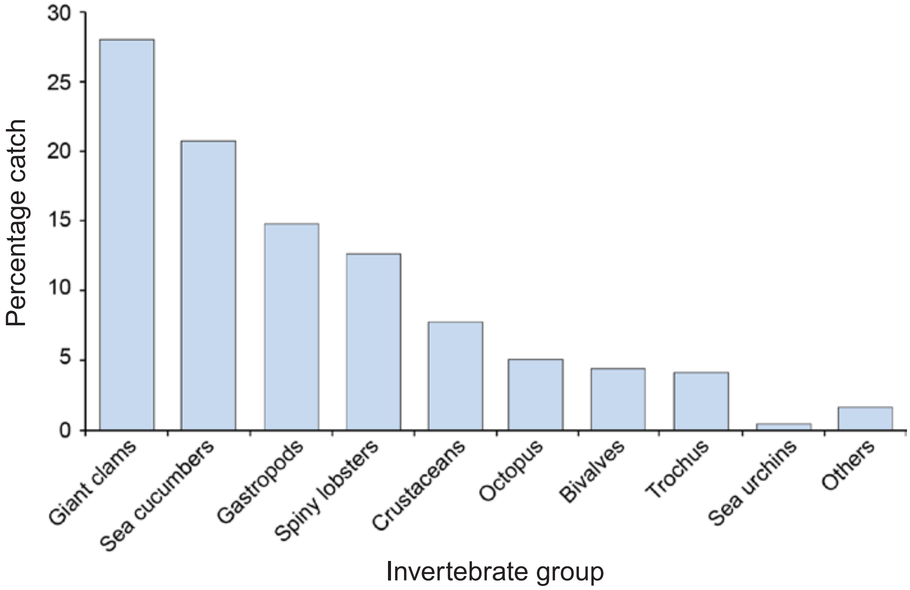


Figure 9.6 The main groups of invertebrates harvested by gleaning and free-diving from shallow subtidal and intertidal habitats in Pacific Island countries and territories (PICTs). Values are percentages of total reported catch (wet weight). Information based on socio-economic surveys conducted in 4–5 coastal fishing communities within 17 PICTs between 2002 and 2008 (source: SPC PROCFish Project).

9.2.2 Recent harvest levels, stock status and estimated sustainable yields

The existing level of harvesting in coastal fisheries throughout much of the world is generally regarded as unsustainable, and in many cases the resources are already over-exploited[73,74]. Despite some notable errors[75], Newton et al.[17] suggested that inshore fisheries, and specifically coral reef fisheries, have collapsed in 18% of tropical island countries worldwide, and are fully- or over-exploited in a further 17% of countries. The sustainability of coastal fisheries depends on the area and quality of critical coastal habitats, relative to the level of exploitation. Many coastal fish and invertebrates are associated with specific habitat types (e.g. coral reefs, seagrasses and mangroves) (Chapters 5 and 6), and decline in abundance after the degradation or loss of these habitats[76]. Major causes of habitat degradation (Section 9.1) generally increase with human population densities, further compounding the ecological impacts of overfishing. However, fisheries exploitation is relatively low within most PICTs compared with other parts of the world, due to relatively small human populations[75].

Estimates of coastal fisheries production in the tropical Pacific in 2007[5] indicate that production totalled ~ 155,000 tonnes across the 22 PICTs, of which 110,000 tonnes resulted from subsistence fishing and ~ 45,000 tonnes from commercial (artisanal) activities (**Table 9.5**). Although subsistence catches exceeded commercial catches in 19 of 22 PICTs (**Table 9.5**), many studies have suggested that subsistence catches are likely to be grossly under-estimated[4,5,8]. Despite the overwhelming importance of subsistence and small-scale artisanal fisheries, there is no uniform system to measure the composition and volume of national fish consumption, or sales of seafood at local markets[4,5]. Therefore, national estimates of coastal fisheries production are often based largely on extrapolation of fish consumption per person derived from household income and expenditure surveys (HIES)[5,7,17].

Table 9.5 Estimated area of coastal habitat and subsistence and commercial coastal fisheries production for all Pacific Island countries and territories (PICTs). Standardised estimates of total fisheries production per area of coastal habitat, and human population density in 2010, are also shown.

PICT	Coastal habitat		Coastal fisheries production (tonnes per year)[c]			Standardised fisheries production (tonnes per km^2 per year)	Population density (no. people per km^2 coastal habitat)[d]
	Area (km^2)[a]	Coral reef (%)[b]	Subsistence	Commercial	Total		
Melanesia							
Fiji*	10,020	?	17,400	9500	26,900	2.68	85
New Caledonia	35,930	12.7	3500	1350	4850	0.13	7
PNG*	22,178	?	30,000	5700	35,700	1.61	135
Solomon Islands	12,635	56.0	15,000	3250	18,250	1.44	43
Vanuatu	1250	56.8	2830	538	3368	2.69	196
Micronesia							
FSM	15,070	21.0	9800	2800	12,600	0.84	7
Guam	240	77.1	70	44	114	0.48	780
Kiribati	4160	47.4	13,700	7000	20,700	4.98	24
Marshall Islands	13,570	14.7	2800	950	3750	0.28	4
Nauru	5	100.0	450	200	650	130.00	2000
CNMI	250	40.0	220	231	451	1.80	82
Palau	2975	23.9	1250	865	2115	0.71	21
Polynesia							
American Samoa	365	17.8	120	35	155	0.42	181
Cook Islands	665	31.6	267	133	400	0.60	24
French Polynesia	15,130	19.8	2880	4002	6882	0.45	18
Niue	55	54.5	140	10	150	2.73	27
Pitcairn Islands	50	80.0	7	5	12	0.24	1
Samoa	465	43.0	4495	4129	8624	18.50[e]	394
Tokelau	210	47.6	375	0	375	1.79	6
Tonga	6160	58.3	2800	3700	6500	1.06	17
Tuvalu	3170	27.4	989	226	1215	0.38	4
Wallis and Futuna	930	45.7	840	121	961	1.03	15
Total	**145,483**	**19.9**	**109,933**	**44,789**	**154,722**	**1.06**	**42**

* Preliminary estimates only; a = information derived from Dalzell et al. (1996)[1] and Institut de Recherche pour le Développement; b = Chapter 5; c = Gillett (2009)[5]; d = SPC Statistics for Development Programme; e = reduces to 16.40 when deep-slope species are removed.

Catches from distinct fisheries sectors, such as the four categories of resources described in Section 9.2.1, are almost never differentiated in national fisheries statistics or household income and expenditure surveys. At best, estimates of volume and value of coastal fisheries are divided into subsistence versus commercial catches[5]. This classification is a major impediment to understanding the contribution of demersal fish, nearshore pelagic fish, targeted invertebrates and shallow subtidal and intertidal invertebrates to food security and livelihoods, and to measuring the success of management to optimise the benefits from these resources. For example, tuna and other pelagic species clearly make a significant but unquantified contribution to coastal fisheries production in Nauru, as well as Samoa and Kiribati[5], and greatly affect estimates of standardised fisheries production for these PICTs (**Table 9.5**).

To address this problem, we used the results from the socio-economic surveys conducted during the SPC PROCFish Project[10] (Appendix 9.1) to disaggregate estimates of national subsistence and commercial catches in 2007[5] into the four categories of coastal fisheries (**Table 9.6**, Appendices 9.1 and Supplementary **Table 9.1** at www.spc.int/climate-change/fisheries/assessment/chapters/12-supp-tables.pdf). The surveys conducted by the SPC PROCFish project also provide information on the status of important families of demersal fish, and the two groups of invertebrates, across a subset of 17 PICTs.

9.2.2.1 Fisheries for demersal fish

Demersal fish dominate the catch from coastal fisheries in the tropical Pacific – they are estimated to yield 86,000 tonnes per year and account for an average of 56% of the total coastal fisheries production, ranging from ~ 30% to 80% among PICTs (**Table 9.6**). As highlighted above, the majority of demersal fish are caught by subsistence fishing.

The status of demersal fish stocks throughout much of the tropical Pacific is poorly known, because of the lack of long-term catch records. However, two broad measures indicate that demersal fish populations are not as over-exploited as in many other developing countries. First, recent estimates of national-level fish catches[5], converted to production per area, show that the majority of PICTs are harvesting < 2 tonnes of seafood per km^2 per year from coastal habitats (**Table 9.5**). Given that only a portion (at most ~ 80%) of the catch comprises demersal fish, such harvests appear to be sustainable (see estimated sustainable yields below). Second, underwater visual surveys of coral reef fish at 4 to 5 sites in each of 17 PICTs show that the biomass of commonly caught species is often in the range of 50 to 250 tonnes per km^2 (**Figure 9.7**), suggesting that stocks of coral reef fish have the potential to sustain substantial harvests in many locations across the region.

These broad indicators need to be interpreted with caution, however. As mentioned earlier, the extent to which estimates of subsistence catches may have been underestimated is unknown[4,5]. Also, low standardised catches for PICTs with large areas of coastal habitat relative to their human populations (**Table 9.5**) do not account for significant spatial variation in exploitation (Box 9.1). In most PICTs, dense human populations occur around provincial centres and urban areas, where intense fishing is likely to lead to localised over-exploitation. Fish stocks may also be over-exploited in areas of low development and low human population densities, if efficient transportation exists that enables increased sale of fish in urban centres.

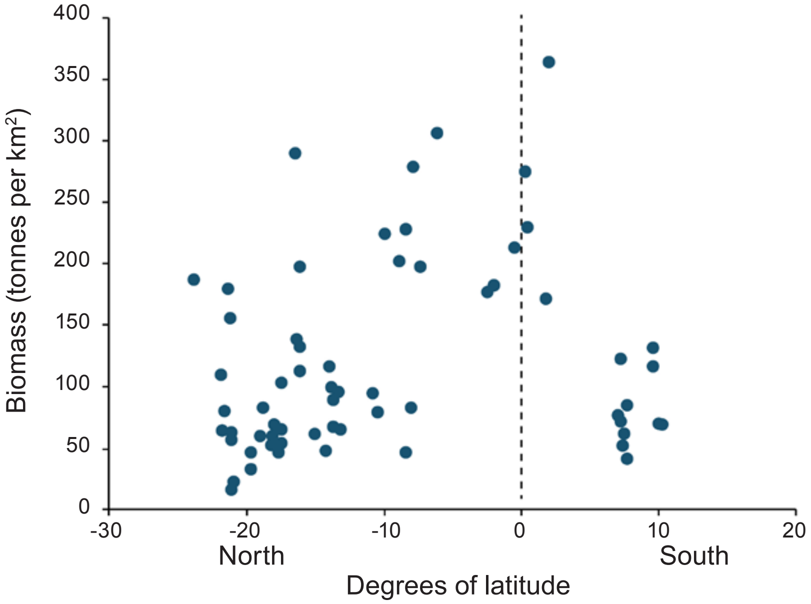


Figure 9.7 Mean biomass (tonnes per km^2) of commonly harvested demersal fish associated with coral reefs at 63 sites from 17 Pacific Island countries and territories (PICTs). Sites are plotted by distance from the equator (degrees of latitude N and S). Information derived from underwater visual census within each PICT between 2002 and 2008 (source: SPC PROCFish Project).

Another important consideration in assessing the status of fisheries for demersal fish is the extent to which fishing is concentrated on different species, especially those considered to play an important role in maintaining the resilience of coral reefs. Foremost among functionally important reef fish, are the herbivorous species that keep reefs relatively free of macroalgae, thereby facilitating the settlement and growth of habitat-forming corals[19]. The role of these fish is especially important given the increasing incidence of coral loss due to climate change[18]. Over-exploitation of herbivorous fish may ultimately lead to a 'phase-shift', where reef habitats become dominated by macroalgae[77,78]. Such phase shifts threaten the status of other reef-associated fish, which is a cause for concern because herbivorous fish (parrotfish, surgeonfish and rabbitfish) comprise a large proportion of the catch in several PICTs (**Table 9.1**). Furthermore, the proportions of parrotfish and rabbitfish in catches are greater than those occurring on reefs (**Figure 9.2**).

A comparison of the recent status of commonly-caught demersal fish with the catch rates of these fish at 63 sites across 17 PICTs, using an approach that integrates many of the key factors outlined above[79], is shown in **Figure 9.8**. The status of demersal fish at 38% of sites was estimated to be poor to medium even though current fishing pressure is low. Such sites appear to have limited potential to produce fish, or productivity may have already been compromised by historical overfishing and/or habitat degradation. Another 25% of sites were in more serious trouble – the status of demersal fish resources was poor to medium and they were subject to high fishing pressure. Demersal fish resources at another 17% of sites had medium to good status but fishing pressure was high and probably unsustainable. Only 19% of sites had medium to good resource status and low fishing pressure.

Table 9.6 Preliminary annual estimated catches in tonnes, and as a percentage of total catch, for the four categories of coastal fisheries in all Pacific Island countries and territories (PICTs). See Appendices 9.2 and Supplementary Table 9.1 (www.spc.int/climate-change/fisheries/assessment/chapters/12-supp-tables.pdf) for the derivation of these estimates.

PICT	Demersal fish		Nearshore pelagic fish		Targeted invertebrates		Sub/intertidal invertebrates		Total catch (tonnes)
	tonnes	%	tonnes	%	tonnes	%	tonnes	%	
Melanesia									
Fiji	17,450[d]	64.9	5270[a]	19.6	630	2.3	3550	13.2	26,900
New Caledonia	2670	55.1	560[a]	11.5	300[e]	6.2	1320	27.2	4850
PNG	14,520	40.7	13,760[a]	38.6	1300[f]	3.6	6120	17.1	35,700
Solomon Islands	8925	48.9	5750[a,g]	31.5	950	5.2	2625	14.4	18,250
Vanuatu	1730	51.3	753[a]	22.4	70	2.1	815	24.2	3368
Micronesia									
FSM	6290	49.9	3560[b]	28.3	30	0.2	2720	21.6	12,600
Guam	33	28.9	77[b]	67.6	0	0.0	4	3.5	114
Kiribati	15,075	72.8	4250[c]	20.5	60	0.3	1315	6.4	20,700
Marshall Islands	2417	64.4	1080[a]	28.8	3	0.1	250	6.7	3750
Nauru	310	47.7	310[c]	47.7	0	0.0	30	4.6	650
CNMI	260	57.6	161[a]	35.7	0	0.0	30	6.7	451
Palau	950	44.9	680[a]	32.2	100	4.7	385	18.2	2115
Polynesia									
American Samoa	92	59.4	47[a]	30.3	0	0.0	16	10.3	155
Cook Islands	146	36.5	240[c]	60.0	0	0.0	14	3.5	400
French Polynesia	3666	53.3	2582[c]	37.5	104	1.5	530	7.7	6882
Niue	62	41.3	75[a]	50.0	0	0.0	13	8.7	150
Pitcairn Islands	10	83.4	1[a]	8.3	0	0.0	1	8.3	12
Samoa	4419	51.2	2550[b]	29.6	0	0.0	1655	19.2	8624
Tokelau	182	48.5	150[c]	40.0	0	0.0	43	11.5	375
Tonga	5245[h]	80.7	650[b]	10.0	0	0.0	605	9.3	6500
Tuvalu	837	68.9	326[b]	26.8	0	0.0	52	4.3	1215
Wallis and Futuna	718	74.7	106[a]	11.0	17	1.8	120	12.5	961
Total	**86,007**	**55.6**	**42,938**	**27.8**	**3564**	**2.3**	**22,213**	**14.4**	**154,722**

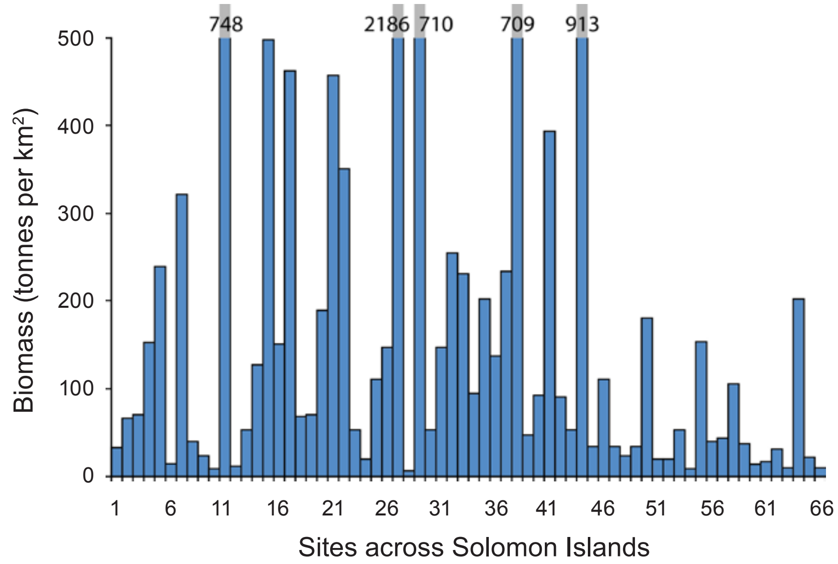
a = Nearshore pelagic fishery dominated by non-tuna species; b = nearshore pelagic fishery comprised equally of non-tuna and tuna species; c = nearshore pelagic fishery dominated by tuna; d = includes deepwater snappers; e = includes mangrove crabs and spiny lobsters sold on local market; f = includes hundreds of tonnes of penaeid shrimp; g = includes 800 tonnes of baitfish; h = includes 700 tonnes of deepwater snappers.

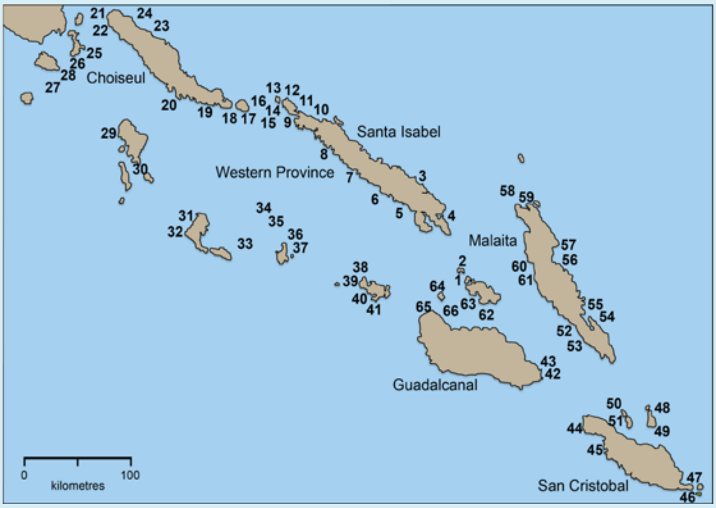
Box 9.1 Within country variation in fisheries resources and exploitation: Case study from Solomon Islands

For much of the tropical Pacific, the fine-scale patterns in the abundance and distribution of coastal fisheries species, and variation in the nature and extent of fisheries activities, are poorly understood. Yet the factors that contribute to fisheries depletion often operate at local scales. For example, the supply of larvae to replenish fished stocks varies at the scale of islands or reefs[259–261]. The size of coastal communities, and the extent of their impacts on coastal fish habitats and stocks, e.g. through sedimentation from poor coastal development (Chapters 5–7), destructive fishing and over-harvesting, also vary at localised scales[81].

How these factors and impacts interact to affect multi-species coastal fisheries within PICTs is still not well understood. Depletion of resources is more likely to be exacerbated where these effects coincide. Without adequate understanding of the factors that affect the status of resources, the incidence of localised stock depletion is likely to increase, leading to reduced resilience of coral reef ecosystems[19].

The information on the abundance of coastal fisheries species at 66 sites across Solomon Islands[262] illustrated here shows the variability in the status of local resources within a country. The highly variable abundance of demersal fish in Solomon Islands is attributable to differences in habitat quality, levels of exploitation, resource management practices, and accessibility to markets[46]. This variation calls for a better understanding of coastal fisheries, including local abundance of key species, quality of fish habitats, socio-economic conditions and cultural practices.





Coral reef habitats are generally expected to yield 3 tonnes of demersal fish per km^2 of reef habitat per year[17]. This yield is the median value for estimates of maximum sustainable production from diverse multispecies coral reef fisheries and, provided that relative species composition remains stable, consistent harvests at this level are likely to be possible. This value is consistent with estimates of long-term (20 years) sustained harvests of 2.9 to 3.7 tonnes per km^2 from Fiji[80]. However, as indicated in **Figures 9.7** and **9.8**, sustainable harvests from coral reefs will vary considerably depending on their condition and productivity. For example, reefs in Fiji with low impacts from land-based activities have been estimated to provide sustained yields of at least 10 tonnes per km^2 per year[81]. Documented yields in 43 locations in the tropical Pacific range from 0.3 to 64 tonnes per km^2 per year[82], and earlier surplus production yield curves suggested a maximum sustainable yield for reef fish in the region of 6 to 20 tonnes per km^2 per year[1].

Although coral reefs are the most significant habitat for coastal fisheries across the region (**Table 9.5**), mangroves, seagrasses, intertidal sand and mud flats also play an important role, both in enhancing productivity of nearby coral reef habitats, and sustaining fisheries production in their own right[83] (Chapter 6). Many of the fish that occupy coral reef habitats as adults reside in other habitats as juveniles[84], although the extent to which these habitats actually contribute to fisheries production on coral reefs is still unknown. The important question is how much of coastal demersal fish production would be lost if there was widespread degradation of mangroves, seagrasses and intertidal flats? To address this issue, catches of demersal fish from distinct habitat types need to be assessed.

If national fisheries production is standardised according to the area of coral reef habitats (rather than all coastal habitats), it exceeds 3 tonnes of seafood per km^2 of reef habitat per year for 10 out of 22 PICTs. Harvest levels of demersal fish are presently

< 3 tonnes per km² of reef per year in American Samoa, Cook Islands, French Polynesia, Guam, Marshall Islands, New Caledonia, Palau, Pitcairn Islands, Solomon Islands, Tonga, Tuvalu and Wallis and Futuna.

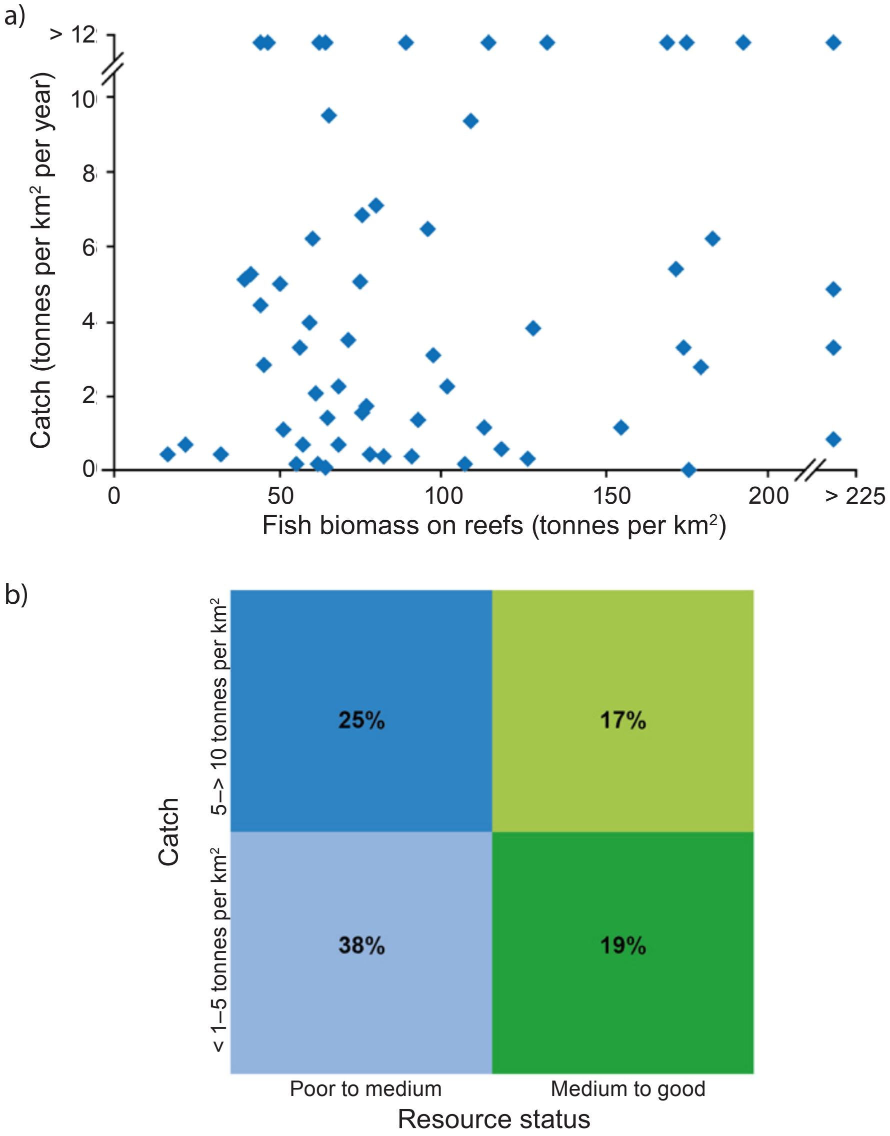


Figure 9.8 Relationships between the status and catches of demersal fish at 63 sites in 17 Pacific Island countries and territories, for the 11 families of fish listed in Table 9.1, based on (a) estimates of fish biomass from underwater visual surveys and socio-economic surveys of adjacent fishing communities; and (b) a more integrated approach to assessing resource status, which combines features of the fish community (size composition from size spectra slopes, differences between cumulative biomass and density dominance curves, relative density of large species, relative biomass of small fish and piscivores, and the ratio of herbivores to carnivores) and site quality (distance from centre of biodiversity, number of reef types, and proportion of the outer-reef surface area) (source: Kronen et al. 2010, Pinca et al. 2011, SPC PROCFish Project)[79,271].

9.2.2.2 Fisheries for nearshore pelagic fish

Large and small pelagic fish also make a significant contribution to the production of coastal fisheries in many PICTs. They are estimated to yield 43,000 tonnes annually, and to make up an average of 28% of total coastal fisheries production, ranging from ~ 10 to 70% among PICTs (**Table 9.6**). In 12 of the 22 PICTs, species other than tuna are estimated to collectively dominate the catch of nearshore pelagic fish (**Table 9.6**). In the remainder of PICTs, tuna (especially skipjack and yellowfin tuna) make up 50% or more of this component of coastal fisheries.

The status of the main species of tuna caught in the nearshore pelagic fishery is monitored closely by the SPC Oceanic Fisheries Programme[85] (Chapter 8). The biomass of the most abundant species in tropical waters, skipjack tuna, remains high and fishing mortality is low. The status of yellowfin tuna is also considered reasonable, with fishing mortality still below the level recommended to achieve maximum sustainable yield, although the impacts of fishing are apparent in the tropical western Pacific (Chapter 8). On the other hand, the present catch rate of bigeye tuna throughout the Western and Central Pacific Ocean is now considered to be unsustainable (Chapter 8). There are few concerns about the status of the other truly oceanic fish species caught by coastal fisheries (mahi-mahi, wahoo, rainbow runner, sailfish and marlin).

The status of pelagic species more closely associated with coastal habitats, such as Spanish mackerel and barracuda, is largely unknown because catch data and knowledge of the population biology and regional abundance of these species are limited. However, Spanish mackerel populations have very low levels of connectivity[86] and there is, therefore, considerable risk of localised depletion.

There is little concern about the status of the small pelagic species used for subsistence and bait. The target species have regular rates of replenishment due to their multiple-spawning reproductive strategy, rapid growth and early recruitment[87]. Even when the pole-and-line tuna fleet in Solomon Islands was operating at its maximum capacity, annual catches of baitfish of around 2000 tonnes per year were considered to be sustainable[59].

The nearshore fisheries take only a tiny fraction of the regional harvests of skipjack and yellowfin tuna, and catches of these two species by the coastal fisheries sector could be increased greatly. The need to do so to provide food security for coastal communities is being actively promoted[4,88]. Ultimately, this increase will involve more of the recommended national sustainable catches of tuna being allocated for this purpose. Such allocations are likely to be in the range of 5–10% of total recommended catches by 2035 (Chapter 12). Increasing fisheries production from nearshore pelagic resources may be used to offset increasing fishing pressure on demersal fish. The fact that tuna and other pelagic species already contribute significantly to coastal fisheries in many PICTs[1,5,10] (**Table 9.6**) suggests that the rates at which demersal fish are being harvested may not be as great as the standardised production figures in **Table 9.5** indicate.

9.2.2.3 Fisheries for targeted invertebrates

Disaggregating the total regional catch from coastal fisheries shows that invertebrates targeted for export commodities make up only about 2% (~ 3500 tonnes) of the total harvest (**Table 9.6**). However, the relatively low catches of targeted invertebrates belie the importance of this fishery, which can contribute significantly to export income in some PICTs[5]. Sea cucumbers often dominate this component of the catch, and the fact that exports of these species comprise processed bêche-de-mer, which typically weighs < 10% of the harvested animals, also masks the importance of this fishery. National records indicate that around 1500 tonnes of bêche-de-mer were exported from the region in 2007. When this catch is converted to live weight, an additional ~ 13,500 tonnes needs to be added to the total harvests[64].

Underwater visual surveys of the densities of sea cucumbers and trochus by the SPC PROCFish Project show that these important resources have been severely overfished in many PICTs[10]. In general, densities of sea cucumbers of high and medium value in fished areas have been greatly reduced, compared with densities in protected and unfished sites in the region, or sites in PICTs where a moratorium has been in place on fishing for these species for at least 10 years[64]. These trends are illustrated by the densities of black teatfish across the Pacific (**Figure 9.9**). Similarly, analyses of the proportion of replicate counts made during surveys of sea cucumber abundance above or below a 'high status' threshold level, show that sea cucumbers have been overfished across most of the region (**Figure 9.10**). The potential yields of sea cucumbers remain low in many parts of the region due to this chronic overfishing. In an effort to restore stocks, some countries (e.g. Palau, PNG, Marshall Islands, Samoa, Solomon Islands and Tonga) have implemented long-term bans on the export of bêche-de-mer at various times. Such measures need to be maintained until densities well exceed the threshold needed for regular replenishment, and appropriate management plans to sustain increased catches are developed[66,89].

Most trochus stocks across the Pacific are also now at very low densities, and experiencing limited recruitment[10]. Only 12 of the 63 shallow water sites surveyed by the SPC PROCFish Project had densities of trochus great enough to support commercial operations (500–600 individuals per ha) (**Figure 9.11**). Interestingly, despite the large number of depleted sites, 44% of sites had 500–600 trochus per ha for at least one of the replicate counts during recent surveys[10]. This density indicates that many areas have potential for recovery provided effective management controls can be implemented to protect the number of adults required for successful reproduction. The potential for rapid recovery is also evident from the fact that viable fisheries for trochus have been established at several places in the Pacific after the introduction of relatively low numbers of adults[68,90,91].

9.2.2.4 Fisheries for shallow subtidal and intertidal invertebrates

The estimated catches of intertidal and subtidal invertebrates of ~ 22,000 tonnes per year, comprising 14% of all coastal fisheries production (**Table 9.6**), may well be underestimates because of the difficulties in effectively capturing the contribution of intertidal gleaning to subsistence catches. Moreover, the use of shallow subtidal and intertidal invertebrates increases when alternative fisheries are inaccessible, or collapse.

There are few reliable indicators of the status of invertebrates gleaned from shallow subtidal and intertidal coastal habitats. However, the densities of the giant clam *Tridacna maxima*, recorded during surveys by the SPC PROCFish Project in 17 PICTs from 2002 to 2008 is a useful one, particularly because giant clams are the invertebrates collected most frequently for food (**Figure 9.6**). Average densities of *T. maxima* were very high (> 5000 clams per ha) in Kiribati and French Polynesia (**Figure 9.12**), due to the suitability of habitats there[92] and low human population density. Elsewhere, however, their average density was < 1000 individuals per ha, and was especially low in PICTs with dense human populations, such as Nauru and Samoa (**Figure 9.12**, **Table 9.4**).

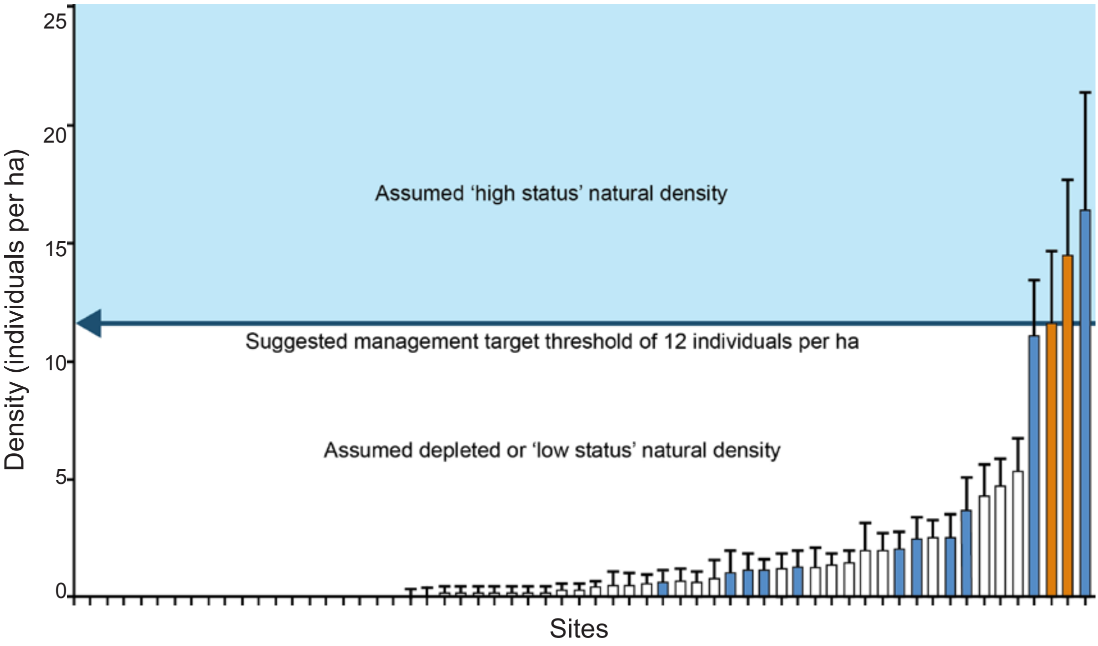


Figure 9.9 Mean density (individuals per ha, +SE) of the high-value black teatfish sea cucumber (*Holothuria whitmaei*) at a range of sites in the tropical Pacific where fishing has occurred (white bars), where fishing has been halted for a decade or more (blue bars), and where fishing has not been recorded in recent history (orange bars) (source: SPC PROCFish Project and, for a single site, S. Purcell, the WorldFish Center).

Whereas some species of spiny lobsters and crabs have proved to be vulnerable to over-exploitation[93], gleaning of infaunal bivalves such as arc and venus shells from soft substrata has remained productive even under heavy fishing pressure[94]. The opportunistic nature of subtidal and intertidal invertebrate fisheries suggests the presence of an element of self-regulation, which prevents localised depletion of most species. Large, rare or highly prized species will still be vulnerable, however.

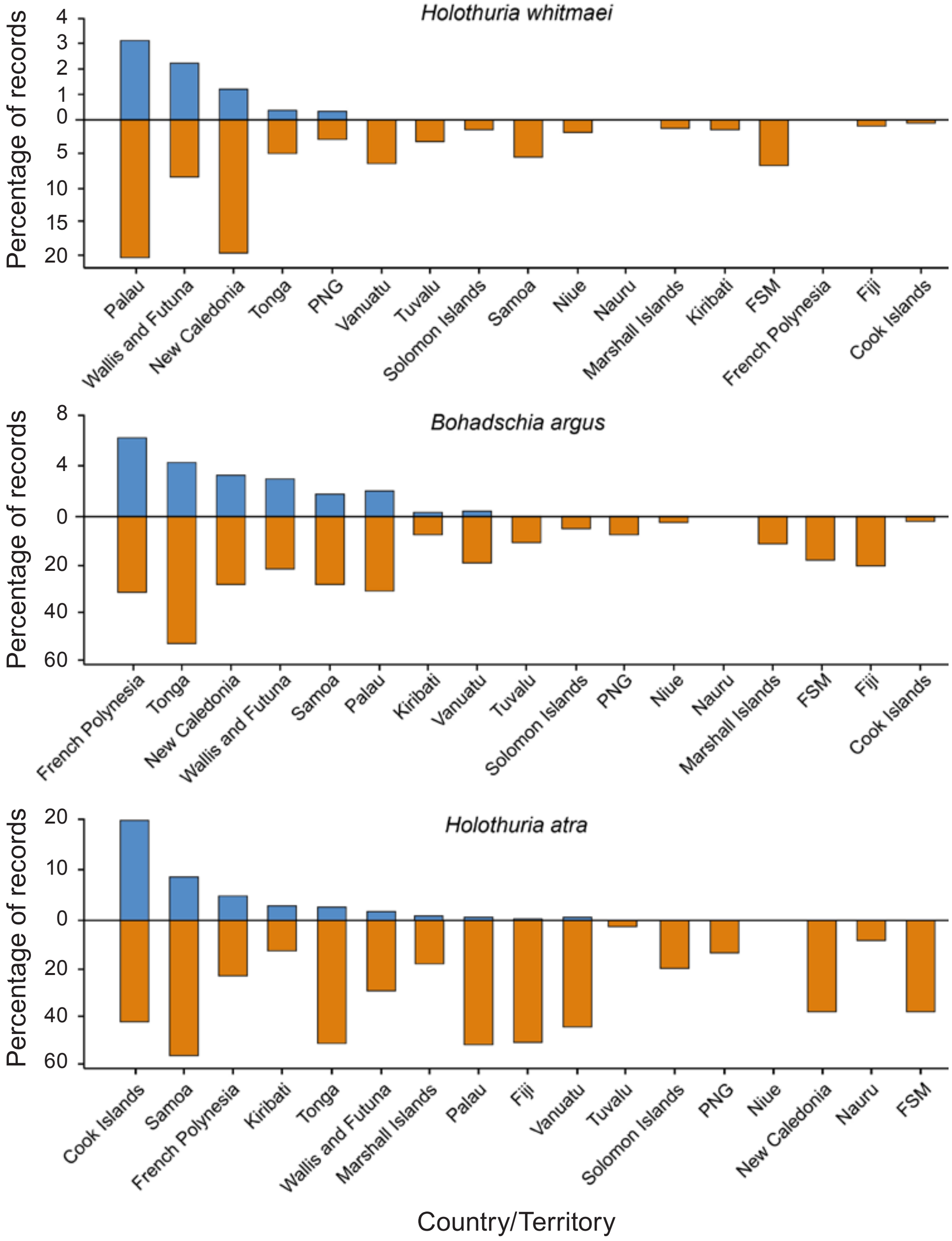


Figure 9.10 Relative status of populations of three 'indicator' species of sea cucumbers across 17 Pacific Island countries and territories (PICTs). The sum of the percentages of the blue and orange portions of each bar gives the total percentage of survey transects where the species was recorded for each PICT. Blue represents abundance at or above a 'high' status threshold and orange reflects a density below this threshold. The threshold is the average of the transects with the 25% highest abundances across 17 PICTs. *Holothuria whitmaei* is a low-density/high-value species, *Bohadschia argus* is a medium-density/mid-value species and *Holothuria atra* is a high-density/low-value species (source: SPC PROCFish Project).

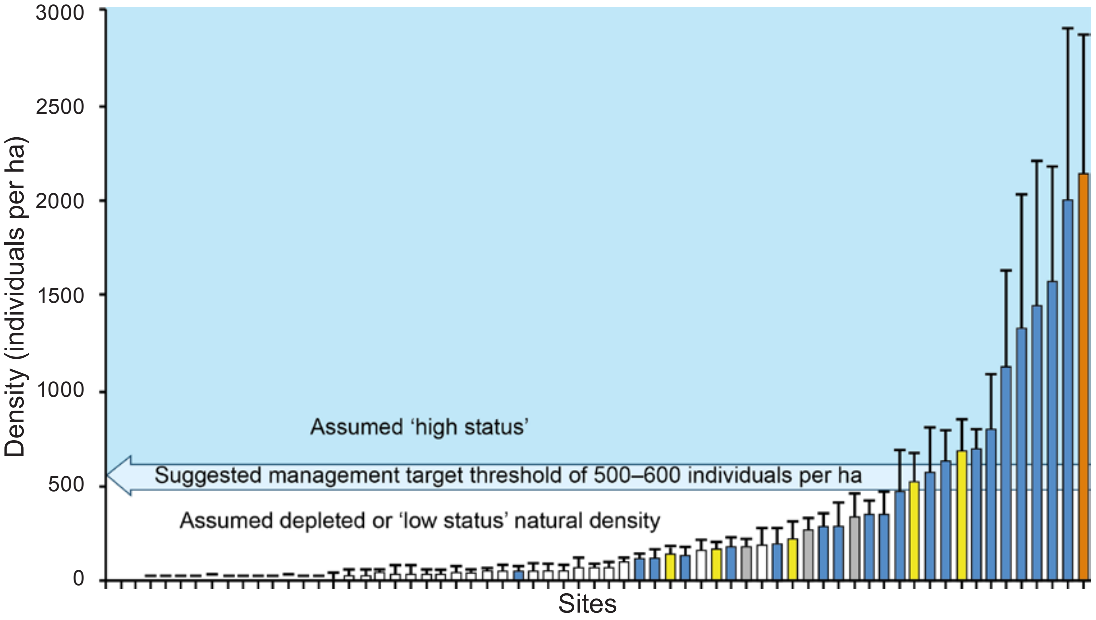


Figure 9.11 Mean density (individuals per ha, +SE) of trochus at a range of sites in the tropical Pacific where fishing has occurred (white bars), fishing is strongly regulated through government and traditional community controls (blue bars), fishing is strongly regulated through community controls alone (yellow bars), trochus have recently been introduced and are subject to national regulations (grey bars), and fishing has not occurred (orange bar). Information derived from underwater visual census in 17 Pacific Island countries and territories between 2002 and 2008 (source: SPC PROCFish Project).

9.3 Vulnerability to climate change

Recent harvests from coastal fisheries are generally within estimated sustainable limits across much of the region (**Table 9.5**) except for some targeted invertebrates. However, there is evidence that catches are not distributed equitably among areas within PICTs and potential target species (Section 9.2.2), and several sites have a poor to medium resource status and high fishing pressure (**Figure 9.8**). The real challenge to sustainability of coastal fisheries will arise as the food requirements of rapidly growing human populations increase by 20–60% over the next two decades[4], and more people seek to fulfil their aspirations to derive livelihoods from fisheries resources[25]. These problems will be particularly acute in Melanesia (Chapters 1 and 12). The difficulties involved in establishing levels of fishing that maximise benefits for people engaged in small-scale fisheries are considerable[24], due largely to the lack of necessary data and understanding of coastal fisheries in the region (Chapter 13). These problems can be expected to increase under the added effects of climate change.

Climate change is expected to alter the potential productivity of coastal fisheries directly, by changing the 'milieu' in which fish and invertebrates live[36,94–96] (Chapters 2 and 3), and indirectly by altering the habitats (Chapters 5 and 6) that provide them with shelter and food[96–99]. The most important direct effects are likely to be due to the projected increases in sea surface temperature and ocean acidification, and changes in ocean currents[36,100] (Chapter 3). The most significant indirect effects will be the projected degradation, fragmentation and loss of coral reefs, mangroves, seagrasses and intertidal flats (Chapters 5 and 6).

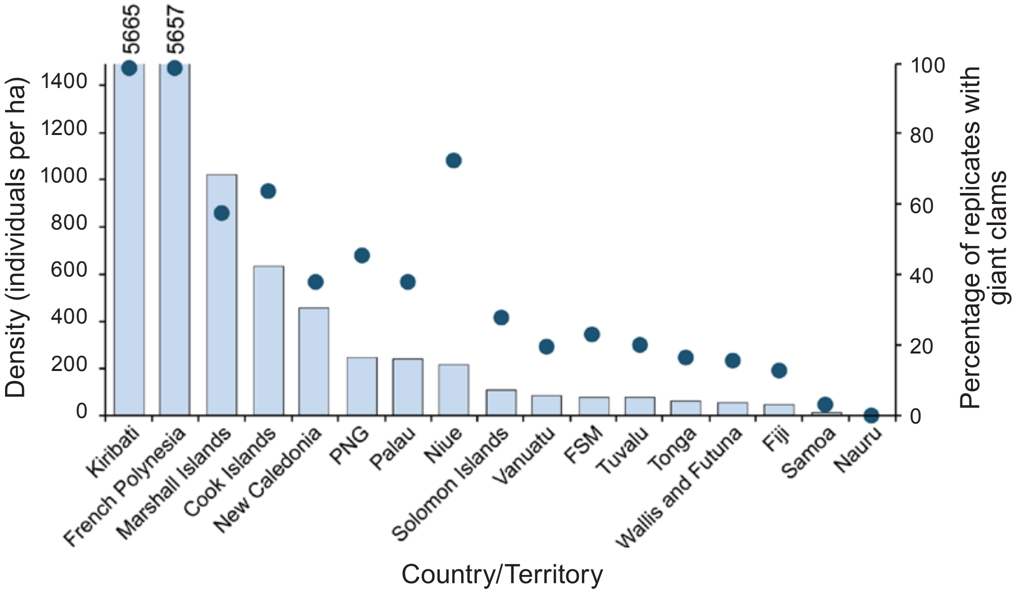


Figure 9.12 Average density (individuals per ha) of the giant clam *Tridacna maxima* for 17 Pacific Island countries and territories (PICTs), and its frequency in the total number of replicate visual underwater survey transects for each PICT (average n = 420). Information collected between 2002 and 2008 (source: SPC PROCFish Project).

Additional environmental changes and severe climatic events, such as increased severity of tropical cyclones, more extreme rainfall events and sea-level rise, could have further direct and indirect effects for some species or life stages[36,37]. For example, tropical cyclones are expected to become more intense in a warmer world[101] (Chapter 2) and cause greater damage to key habitat-forming species, such as corals[102] and seagrasses (Chapters 5 and 6). The effects of cyclones are expected to compound damage to coral reefs caused by bleaching and acidification. Indeed, cyclones are known to reduce abundance of fish due to loss of critical habitat[76,103]. Overall, the indirect influence of cyclones on the physical and biological complexity of fish habitats is expected to have greater effects on coastal fisheries than the direct effects of more intense cyclones, and increases in rainfall and sea-level rise.

The direct and indirect effects of climate change on coastal fish and invertebrate species will vary depending on their biology and ecology[36]. For example, recent effects of climate-induced coral loss on reef fish vary depending on their reliance on live corals for food, shelter and/or recruitment[104]. Butterflyfish, and certain species of damselfish, cardinalfish and coral-dwelling gobies have the greatest dependence on live coral and are directly at risk from loss of corals[104]. Other fish may also be particularly susceptible to climate change owing to their sensitivity to changes in temperature or ocean chemistry[106]. However, specific tests of sensitivity of reef fish to projected environmental changes are restricted to a few species and mostly one to two families[105–107]. It is unclear how the results from these limited experiments will relate to species targeted by fisheries, which are often larger and more mobile.

The vulnerability of key fisheries species to changes in environmental conditions (temperature, ocean acidification, ocean circulation and nutrient supply) and habitats depends on their exposure, sensitivity, and capacity to modify the potential impact (Chapter 1). Exposure is the magnitude and extent of projected changes in environmental variables and/or habitats relative to the existing conditions, whereas sensitivity refers to the likely responses of the species to the projected changes, in terms of local abundance, size or productivity (Chapter 1). The potential impact of projected changes on species is moderated by the species ability to alter its physiology, behaviour and/or distribution to cope with change. Species with a high sensitivity to changes in environmental conditions and habitats, which are unable to adapt, for example by switching to other prey, living in slightly different habitats, or evolving increased tolerances, are most vulnerable and potentially at risk of local extinction due to climate change[108,109].

Changes in the distribution and abundance of coastal fisheries resources are also expected to the social and economic fabric of Pacific Island nations, depending on their willingness and capacity of communities to alter and/or diversify fisheries activities, their access to alternative sources of food, and alternative opportunities to earn income[26,110,111]. However, with the exception of possible risks to changes in the incidence of ciguatera fish poisoning, this chapter focuses on the vulnerability of coastal fisheries resources to climate change, not the socio-economic effects. The risks to food security and livelihoods of coastal communities in the region are assessed in Chapter 12.

9.3.1 Vulnerability to the direct effects of climate change

9.3.1.1 Water temperature

Changes in water temperature have a major influence on most coastal fish and invertebrates because they have limited capacity to maintain an independent body temperature. Indeed, variation in temperature tolerances[112–114] has a major bearing on the geographic ranges[115–116] and general biology[117] of fish and invertebrates. As sea surface temperature (SST) increases due to global warming, populations of thermally-sensitive marine organisms are expected to shift towards higher latitudes, whereas populations that can endure warmer waters may exhibit changes in their life history traits, such as growth rates and longevity[36]. Global warming is likely, therefore, to have significant consequences for the distribution and abundance of key fish and invertebrate species, as well as productivity and composition of coastal fisheries throughout the region.

Exposure and sensitivity

Average global atmospheric temperatures have increased by > 0.7°C over the past 100 years (Chapter 2), with the current rate of warming far greater than at any time during the last 1000 years[27]. In the tropical Pacific Ocean, mean SST is expected to increase substantially by the end of this century (Chapters 2 and 3). Even under a low (B1) emissions scenario, average SST in the region is likely to increase by 0.7°C by 2035, and 1.0–1.5°C by 2100 relative to 1980 to 1999. However, if recent increases in global CO_2 emissions continue unabated (represented by the A2 scenario), average SST for the tropical Pacific may increase by as much as 2.5–3.0°C. The projected surface warming also has a spatial pattern, with greater warming in the eastern than western equatorial Pacific and less warming in the southeast Pacific (Chapters 2 and 3).

Many marine species can withstand a considerable range in water temperature, as apparent from their large geographic and latitudinal distributions[118,119]. Even within their limited home ranges, tropical and subtropical organisms are regularly exposed to a range of temperatures due to diurnal and seasonal cycles of warming and cooling. Diurnal variation in water temperatures is particularly apparent in shallow coastal habitats, where it can fluctuate by > 14°C throughout the day[120].

In contrast, water temperature typically varies less than 1°C per day for deep subtidal habitats[121] and the average daily SST range in the ocean is only about 0.2–0.3°C[122]. Seasonal variation in SST in the tropical Pacific Ocean is generally < 7°C (Chapter 3), but marked increases in solar radiation can heat shallow water bodies rapidly during summer. These habitats also cool quickly during cold winter nights. Seasonal variations in SST can also be amplified by large-scale climatic events on decadal cycles (Chapter 2). For example, in the eastern tropical Pacific, the El Niño-Southern Oscillation can increase SST by up to 2.0–3.0°C during El Niño events and cause similar reductions during La Niña episodes[123,124] (Chapter 3).

Tropical marine fish and invertebrates are sensitive to variations in SST because temperature regulates metabolism and development, and limits activity and distribution. Many of these species are relatively tolerant of short-term changes in ambient temperature, and tend to live well within their critical thermal limits[125,126]. However, virtually all organisms have a 'hump-shaped' temperature-performance curve, which shows how growth, reproduction or movement increases with SST elevations, until the optimal temperature is reached, after which performance declines[117,127] (**Figure 9.13**). The rate of change in performance with increasing SST is often more pronounced beyond the optimal temperature, up until the point at which it becomes lethal. Therefore, small increases in SST above the thermal optimum can have important consequences.

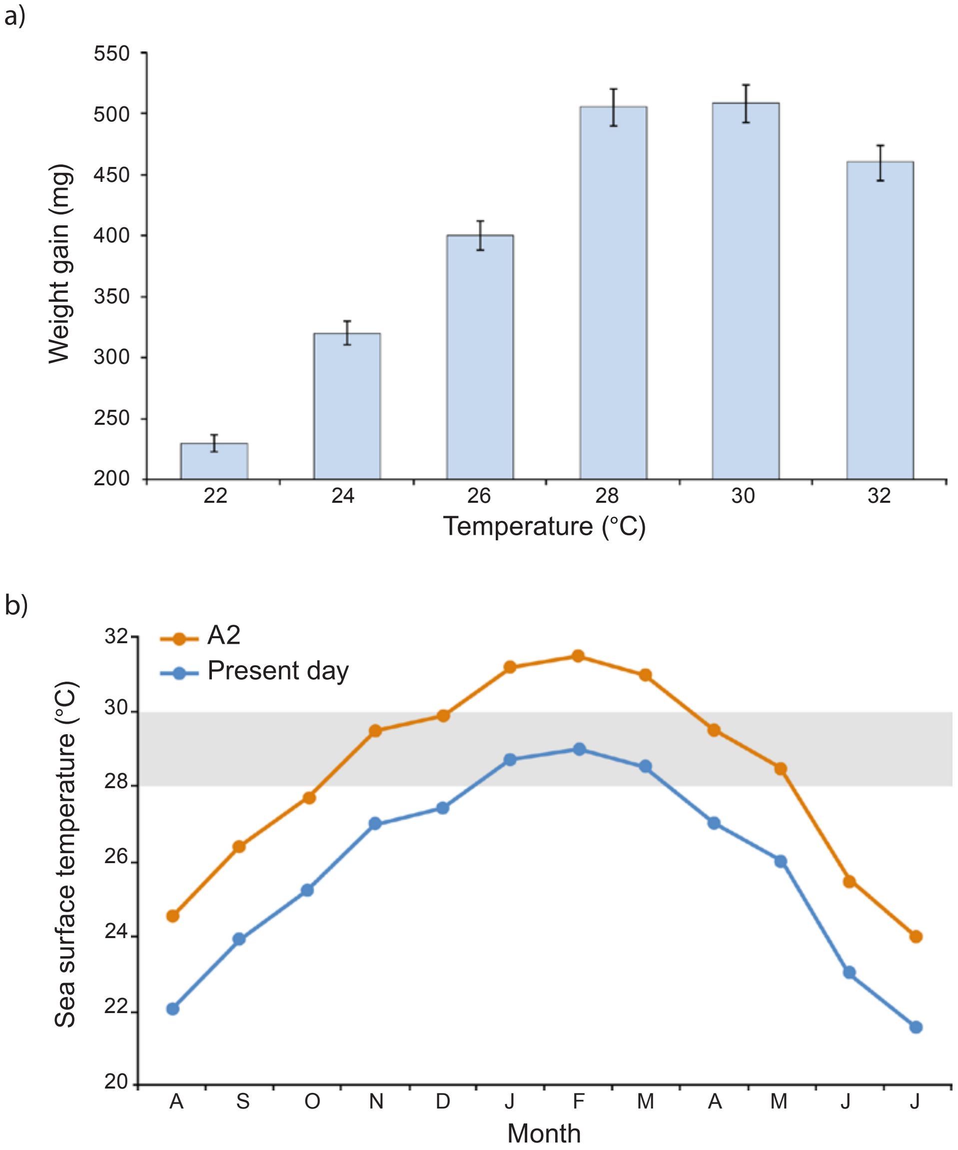


Figure 9.13 (a) Mean weight gains (mg ±SE) for larval damselfish *Acanthochromis polyacanthus* reared in captivity at 29°C, and then maintained at different temperatures for 6 weeks from one week-post hatching (Liao, Coker and Pratchett, unpublished data). The thermal optima (at which weight gains were maximised) appear to be 28–30°C; (b) present-day and increased mean monthly sea surface temperatures (SSTs) expected to occur by 2100 under a high (A2) emissions scenario – the shaded area represents the current thermal optima (28–30°C) for *A. polyacanthus* at Orpheus Island, central Great Barrier Reef, which corresponds with the present-day mean summer maximum SST (source: Munday et al. 2008)[105].

The extent to which increasing SST will have positive or negative effects on individual species depends on whether water temperatures are moving towards or away from the thermal optima for a particular population[128]. Increases in overall SST may increase growth and production during months and seasons where temperatures are presently well below the optimum (**Figure 9.13**). However, there are likely to be increased risks to fish populations in seasons where SSTs begin to exceed thermal optima[129]. Indeed, projected increases in SST of 1–3°C will take summer maximum temperatures beyond the range at which growth, reproduction and metabolic rate are maximised for some populations[105,130,131].

The main effect of rising water temperatures on fish relates to increases in their metabolic processes, and limitations in meeting the associated higher demands for oxygen (O_2)[117]. The metabolic rate of an individual reflects the total energy expended for ingestion and digestion of food, growth, maintenance and activity[113]. Metabolic activity for fish increases in direct proportion to moderate increases in ambient temperature[119,132–134]. However, with increasing SST, there is a decrease in available dissolved O_2, whereas a fish's demand for O_2 is increasing[116,135]. Consequently, oxygen becomes a limiting factor in cardiovascular performance[136]. Decreased capacity of the ventilatory system to keep pace with increased oxygen demands at higher temperatures is therefore the key physiological mechanism controlling an organism's thermal tolerance, and determines its response to increasing SST[116,117].

The sensitivity of the aerobic system to increased SST is unknown for most tropical marine species. However, sensitivity to increasing temperature has been shown to differ greatly among five species of coral reef fish[130]. In two cardinalfish, the maximum oxygen uptake for aerobic activity (aerobic scope) declined dramatically with an increase of 2–4°C. Aerobic scope was reduced by nearly half at 31°C compared with 29°C and virtually all capacity for additional oxygen uptake was exhausted at 33°C. In contrast, three species of damselfish were relatively tolerant of the same increase in temperature and retained over half their aerobic scope at 33°C. These results suggest that adults of some species are highly sensitive to small increases in temperature, whereas other species may be quite tolerant to the increases of 2.5–3.0°C in SST projected to occur under the A2 emissions scenario by the end of the century.

Potential impact and adaptive capacity

Projected increases in SST within shallow coastal environments of up to 2.5–3°C by 2100 are expected to have limited direct effects on survival of adults for most fisheries species, but may still interfere with reproduction, recruitment and juvenile growth[131,137,138]. Even temperature increases of 1–2°C can affect the reproductive performance of some reef fish[131,138] and are likely to lead to shifts in the timing of spawning, and possibly falling egg production, in some populations. Where reproductive development and spawning synchrony are cued to temperature, seasonal changes in SST may lead to alterations in the timing of breeding[36]. Increases in average SST could also lead to more protracted or more irregular opportunities for successful reproduction, depending on how close present-day SSTs are to the optimum temperatures[36]. Species that use photoperiod as the major cue for spawning[137] are less likely to adjust the timing of reproduction to suit the thermal environment. For these species, reproductive success may be compromised if higher water temperatures cause egg production to be impaired[139], increase embryonic mortality[138], or lead to a mismatch between the timing of spawning (set by photoperiod) and the optimal conditions in the plankton for survival and dispersal of larvae (set by temperature)[140].

Increases in ambient temperature, and corresponding increases in food demands, are also expected to affect the survival of offspring, especially during pelagic dispersive phases. Larval fish grow and develop more rapidly at higher temperatures[37], meaning that they may experience lower rates of mortality[141]. However, under higher SSTs, entire cohorts of larval fish may not be able to obtain sufficient food to sustain their rapid growth and development, leading to more frequent recruitment failure[37,142].

Increases in SST above the thermal optima are also expected to reduce individual performance, leading to declines in growth and reproduction. For example, a 3°C increase in SST would mean that optimal temperatures for growth of the damselfish *Acanthochromis polyacanthus* would be exceeded for at least half the year (**Figure 9.13**). If such effects are also typical of harvested species, decreases in fisheries production can be expected. A decline in summer performance of fish species may, however, be offset by increased growth during cooler months. Ambient temperatures may be below the local optima at such times, except where the warming causes mean monthly SST to exceed normal summer optima for extended periods. Thus, unless species can acclimatise or adapt to such temperature increases, an overall reduction in biomass may occur. The capacity of most tropical marine fish and invertebrates to acclimatise or adapt to rapid temperature change is unknown[143]. This serious gap in our knowledge must be filled before projections about the consequences of future increases in SST on demersal fish and invertebrates associated with coral reefs can be made with confidence.

Many tropical marine fish have large latitudinal ranges that extend across temperature gradients greater than the expected increases in SST due to global warming. Life history traits of some species covary in a predictable way with these latitudinal and temperature gradients[144,145]. Although there are many exceptions, reef fish species tend to be shorter-lived and reach smaller maximum sizes in equatorial areas compared with the subtropics[36]. Juveniles are also expected to reach their asymptotic size at a faster rate at higher temperatures. Consequently, we might expect that as SST increases, life history traits of populations in the subtropics will become more like those exhibited in populations already living at higher temperatures (e.g. shorter-lived and smaller maximum sizes), with knock-on effects on fisheries production. However, life history traits are also influenced by food supply, and population density and structure, which vary at a range of spatial scales, and might themselves be influenced by increased SST. Thus, projecting the likely effects of elevated temperature on life history traits is extremely difficult[36].

The main way that fish and invertebrates are likely to respond to altered environmental regimes is to shift their geographic (especially latitudinal) ranges[115,146,147]. Poleward shifts in geographic ranges have been observed for many marine organisms[115,148–150]. However, the ability of species associated with coral reefs to establish permanent populations at subtropical latitudes will depend on their specific requirements for food, shelter and reproduction, their tolerance to lower minimum temperatures in winter, and competition from established subtropical species[36].

Vulnerability

The net effects of increasing SST on growth, abundance and productivity of coastal fisheries species are uncertain[100], but moderate increases in temperature are likely to affect reproductive output as well as the development and survival of larval stages. As a result, fished stocks may become more vulnerable to periodic collapse due to greater inconsistency in the supply and survival of larvae. This threat would be compounded by changes in population connectivity caused by more rapid larval development; in particular, the opportunity for larval replenishment from distant stocks in cases of local overfishing is likely to be reduced[37]. Productivity of coastal fisheries is also likely to be reduced as a result of the effects of higher SST on metabolic rates. Fish and invertebrates are expected to need more food, given their higher rate of metabolism in warmer waters, under circumstances where changes in climate are projected to reduce nutrient inputs (Chapters 3 and 4) and degrade benthic habitats (Chapters 5 and 6) (as discussed below). Overall fisheries production is expected to decline with increasing SST, except in locations of local nutrient enrichment[99] (Section 9.3.3).

Photo : Hemis.fr/SuperStock

Checking a fish trap in Polynesia

An independent global analysis has also concluded that the redistribution of fisheries species associated with increasing SST and shifts in climate is expected to have significant impacts on fisheries production of tropical countries[147]. Geographical shifts in the distribution and abundance of major fisheries species, combined with projected changes in primary production, are expected to cause a decline of up to 40% in fisheries production in the tropical Pacific under high emissions scenarios[147]. However, these estimates fail to take account of habitat requirements that will limit latitudinal shifts of many reef species; only generalist species that are loosely associated with coral and reef habitats are expected to move poleward to escape rising SST in the tropics.

9.3.1.2 Ocean acidification

Ocean acidification, caused by the uptake of carbon dioxide (CO_2) emissions by the ocean (Chapter 3), is a serious threat to marine ecosystems[151,152] and fisheries[153]. Additional CO_2 dissolved in the ocean reacts with sea water to form weak carbonic acid, causing pH to decline and reducing the availability of dissolved carbonate ions required by many marine calcifying organisms (particularly corals, other invertebrates and coralline algae) to build their shells or skeletons[154] (Chapter 3). Ongoing ocean acidification will reduce growth and survival of many calcifying organisms and affect the food webs that depend on them[152,155] (Chapters 4 and 5). The reduction in ocean pH could also have a range of direct effects on coastal fish, from increased metabolic demands to developmental problems[156].

Exposure and sensitivity

Atmospheric CO_2 concentrations have increased from ~ 280 ppm in pre-industrial times to ~ 390 ppm today, causing the average pH of the ocean to decline from 8.2 to 8.1[157]. Depending on emissions scenarios, CO_2 concentrations are projected to reach 540–800 ppm by the end of the century[157] (Chapter 1), resulting in a further decline in average ocean pH of 0.3 to 0.4 units[158] (Chapter 3). The projected emissions of CO_2 are expected to make the ocean more acidic than at any time in the past 800,000 years[159]. Changes in global ocean pH will be most apparent in open ocean waters, where pH naturally varies by only 0.1–0.2 units depending on biological production and nutrient inputs. In contrast, pH is naturally variable in coastal habitats. For example, pH ranges up to 0.8 units throughout the day in shallow coral reef habitats due to diurnal patterns of respiration, photosynthesis and calcification[160]. The potential for dissolution of carbonate within extensive coral reef frameworks to partly buffer the effects of ocean acidification is also unknown, but this effect may limit declines in pH of near shore, shallow carbonate systems.

Many coastal invertebrates (including molluscs, echinoderms and crustaceans) are expected to be sensitive to any changes in the pH of nearshore waters because their exoskeletons, shells or skeletal elements are composed of aragonite or high-magnesium calcite[161], both of which have low saturation states in sea water. Levels of acidification that could occur in the world's oceans within the next 50 years are below the levels that have been shown (in controlled experiments) to reduce calcification rates for a wide range of species[162–167]. Calcifying molluscs that have been subject to reduced pH, either under experimental conditions or in marine habitats with naturally low pH, usually have much thinner shells, reduced growth and lower survival rates[166,168]. For commercially important invertebrates in the tropical Pacific that are harvested for their shell (e.g. trochus), these weaknesses may simultaneously affect the size of populations as well as the individual value of each animal.

Reduced calcification rates could also possibly affect spicule formation in sea cucumbers[64], thereby reducing growth or increasing susceptibility to predation. In contrast, decapod crustaceans (spiny lobsters, crabs and shrimp) may be capable of higher rates of calcification in acidified conditions. These animals have an external organic layer (epicuticle), which separates their carapace from sea water and can effectively regulate internal pH at the site of calcification[161]. Growth and survival of some decapods declines at low pH[169], however, which may reflect the increased physiological costs associated with adverse environmental conditions.

The internal bony skeletons of fish are unlikely to be affected to the same degree as the external skeletons of invertebrates. Fish bones are composed of calcium phosphate, not calcium carbonate, and the skeletons of fish may be protected from external pH changes by the fish's own internal acid-base regulation[170]. Fish otoliths (ear bones) are more likely to be susceptible because they are composed of aragonite. However, otoliths may also be protected by active acid-base regulation of the endolymph. Indeed, one recent study found that otolith calcification increased in larvae kept at low pH, possibly as a result of increased carbonate concentrations in the endolymph caused by acid-base regulation[171]. Whether acidification affects otolith growth or development in other species is unknown, but any effects could be significant because otoliths are important for individual orientation and hearing, especially during the dispersive larval stage[37].

Increased CO_2 not only acidifies the ocean, it also decreases the pH of animal tissue[156,170,172]. Fish compensate for this acidification with bicarbonate accumulation and counter-exchange of ions across the gills[173,174]. Consequently, most fish tolerate a wide range of dissolved CO_2 and pH levels[156,172,175]. Although compensation of acidosis is not detrimental in the short-term, ultimately, it might have some physiological costs, especially for species or life stages with high metabolic demands[156] or when compounded by higher metabolic demands at elevated temperatures[117].

Enzymatic changes consistent with a shift from aerobic to anaerobic metabolic pathways have been observed in a temperate marine fish exposed to CO_2 levels ~ 4.5 times above average[176]. Also, significant declines in aerobic scope have been detected for two species of coral reef fish exposed to CO_2 levels ~ 2.5 times above ambient[177]. In the latter study, the effect on aerobic scope of 1000 ppm CO_2 was similar to that caused by a 3°C increase in water temperature above the summer average. This effect indicates that ocean acidification could have consequences for the aerobic performance of coral reef fish in addition to those expected to occur as a result of increasing SST[130]. Limited research on marine invertebrates suggests that there is considerable variation in the extent to which species can regulate internal pH to withstand short-term changes in ambient conditions[161,178]. It is not clear whether this regulation will enable species to withstand projected changes in ocean chemistry.

Potential impact and adaptive capacity

Direct effects of elevated CO_2 are likely to be greatest during the early life history phases of marine fish and invertebrates[156,179]. Indeed, fertilisation of eggs[180] and development of larvae[168] of some invertebrates is influenced significantly at the range of CO_2 concentrations that are projected to occur by 2100. Even moderate increases in CO_2 concentrations (560 ppm leading to a decline in pH to ~ 7.9) reduce the growth of adult gastropods and sea urchins due to reduced calcification[168]. In contrast, a study of reef fish, using CO_2 levels relevant to climate change projections (up to 1000 ppm), did not detect any negative effects on the growth or development of clownfish larvae[106]. Clearly, more research is needed to test the effect of elevated CO_2 on the early life stages of coastal fish across a broader range of species, and to examine possible synergistic effects of elevated temperature and CO_2.

A greater concern for coastal fisheries in the tropical Pacific is the effect that elevated CO_2 levels could have on the sensory ability of larvae. Clownfish larvae exposed to CO_2-acidified water lose their ability to distinguish olfactory cues from preferred settlement habitat[106], or to detect and avoid the smell of predators[181], at the end of their larval phase. When reared in water treated with 1000 ppm CO_2, the larvae became strongly attracted to chemical cues they normally avoided. The larvae of many marine fish use chemical cues for a wide range of important behaviour decisions, including navigation to reefs and selection of settlement sites[182–184]. Impairment of this process by ocean acidification could have serious implications for the replenishment of adult populations and patterns of population connectivity in coral reef ecosystems.

Despite the fact that acclimatisation or adaptation are important considerations when assessing the vulnerability of fish and invertebrates to projected climate change[18,152,185], the potential for most marine organisms to adapt to a rapid reduction in ocean pH has rarely been tested. Ocean pH has changed very little over the past 800,000 years[159], and so it might be expected that marine organisms lack genetic variation necessary for rapid adaptation to changes in seawater chemistry[151].

Vulnerability

Declines in global ocean pH and associated decreases in the availability of carbonate ions will cause reduced calcification, growth and survival of calcifying organisms in the absence of rapid and effective adaptation. Key fisheries species that are likely to be directly affected include bivalves (giant clams), gastropods (trochus), sea cucumbers and sea urchins. If greenhouse gas emissions continue unabated, as projected by the A2 scenario, these calcifying organisms are unlikely to be able to sustain significant commercial and subsistence fisheries into the future.

Ocean acidification is also expected to compound the negative effects of increasing SST for fish and invertebrates. Impaired larval behaviour caused by elevated CO_2 could also affect the replenishment of populations, increasing the risks of decline in the stocks that support coastal fisheries.

9.3.1.3 Ocean currents

Changes to ocean circulation and current patterns throughout the tropical Pacific, expected to occur as a consequence of climate change (Chapter 3), could affect the production of coastal fisheries in two main ways. Firstly, currents, eddies, and other hydrodynamic features play an important role in the retention and dispersal of pelagic larvae[186–188]. Any changes to circulation patterns as a result of climate change could have fundamental effects on the spatial and temporal patterns of larval settlement, and the degree of connectivity among meta-populations[37]. Secondly, currents play an important role in providing nutrients and food to coastal habitats that are often limiting. In the waters surrounding PICTs, nutrient supply influences the production and distribution of phytoplankton and zooplankton[189,190] (Chapter 4), which are integral parts of the food webs supporting both larval fish and planktivorous adult fish residing on reefs. Changes to primary and secondary productivity caused by altered ocean circulation are expected to affect the growth and survival of these two categories of fish[191–193] and biological production throughout the entire ecosystem[99].

Exposure and sensitivity

The South Equatorial Current (SEC), which flows westward just south of the equator, is a major oceanographic feature of the tropical Pacific Ocean. The SEC generates significant surface currents and eddies, and drives vertical mixing and upwelling of nutrient-rich waters (Chapter 3). The transport volume of the SEC is expected to decrease in strength by 3–5% under the B1 and A2 emissions scenarios by 2035, by ~ 10% under B1 by 2100, and ~ 20% under A2 by 2100 (Chapter 3). The eastward-flowing South Equatorial Counter Current (SECC) is also expected to decrease in velocity and change direction. These changes are expected to take time to appear – flow of the SECC is projected to decrease by < 5% under the B1 and A2 scenarios by 2035. However, flow is expected to decrease by ~ 30% under B1 by 2100, and by 60% under A2 by 2100. The surface flow is also likely to turn towards the south, reducing the penetration of the SECC to the east (Chapter 3). Consequently, associated eddies and upwellings are expected to decline. The projected increases in SST are also likely to enhance stratification and reduce vertical mixing[35,194] (Chapters 3 and 4).

Such large-scale changes to circulation patterns have potential to influence dispersal and survival patterns of marine fish larvae (**Figure 9.14**), while reductions in vertical mixing and supply of nutrients to shallow coastal habitats could reduce the productivity of coastal ecosystems. In nearshore environments, diminished supplies of nutrients from the ocean may be compensated by increased inputs from runoff, which are expected to increase with climate change (Chapters 2 and 7).

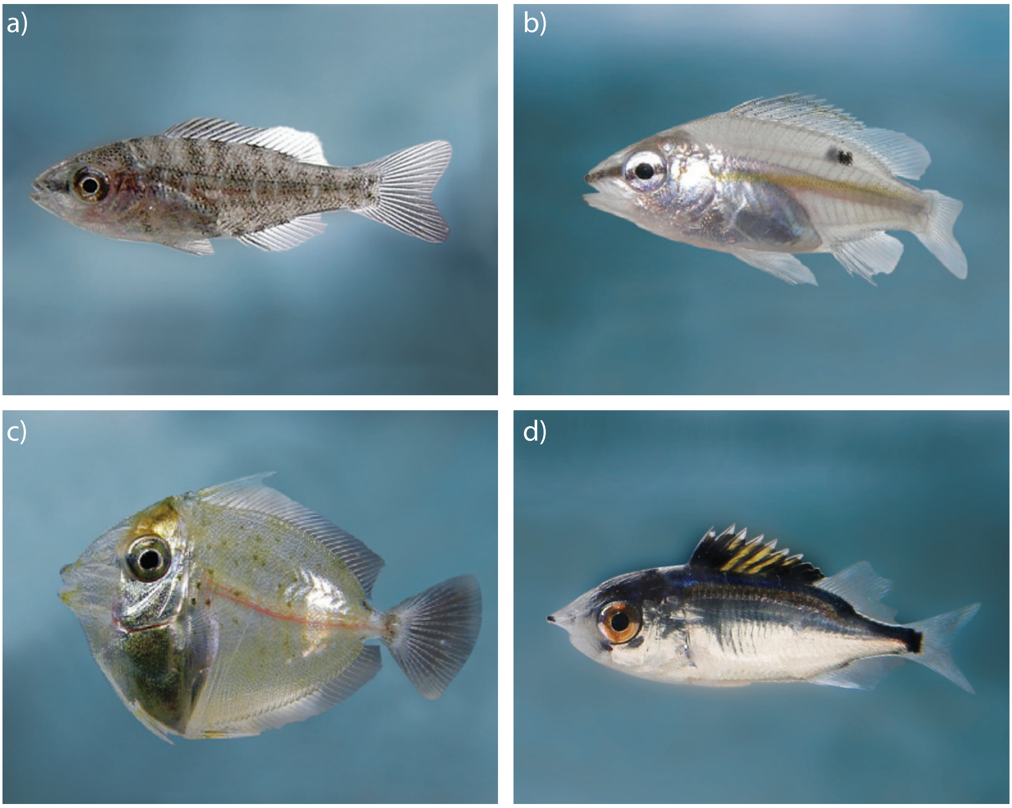


Figure 9.14 Postlarvae of demersal fish families from the tropical Pacific (a) Lethrinidae, (b) Lutjanidae, (c) Acanthuridae, and (d) Holocentridae (photos: Colin Wen).

Fisheries production is sensitive to changes in ocean circulation, and especially the strength and persistence of upwellings. Approximately 25% of total global marine fish catches are concentrated in areas where the strong vertical mixing of ocean layers brings nutrients to the surface[99]. Increased thermal stratification of the ocean layers reduces the delivery of nutrients from the deeper, cooler waters to coastal habitats[35,194,195] (Chapter 3). This reduction in supply of nutrients decreases the productivity of the plankton communities that provide an important food source for many coastal fish and invertebrates, and which underpin the food webs sustaining large pelagic fish species (Chapter 4). In the Western Pacific Warm Pool and the Archipelagic Deep Basins provinces of the region[196], where the larger PICTs are situated, phytoplankton production is estimated to decline by 5–8% under the B1 and A2 emissions scenarios in 2035, by 9–20% under B1 in 2100, and by 9–33% under A2 in 2100 as a result of reduced vertical mixing[197] (Chapter 4). The productivity of planktonic communities can also be reduced at higher temperatures[190] (Chapter 4). Reduced availability of food, combined with increased metabolic rates at higher temperatures[36], may lead to starvation of fish and invertebrates, especially among early life history stages.

Impact and adaptive capacity

Changes to major ocean currents and wind-driven surface currents, upwelling, eddies, and other hydrodynamic features of the tropical Pacific Ocean could have important effects on the dispersal and survival of coral reef fish larvae[37]. Connectivity among distant reefs and islands is likely to be compromised, so that stocks are expected to be more reliant on local reproduction to replenish populations. Projected declines in the strength of surface currents (of up to 50%) will reduce the transport of pelagic larvae among disparate islands and reefs and declines in the strength of eddies may reduce the retention and accumulation of larvae within the vicinity of appropriate settlement habitats. Connectivity is likely to be reduced further by increased fragmentation of coastal habitats (Chapters 5 and 6), and declines in the pelagic duration for larvae (as discussed previously). Management to avoid localised depletion of fisheries stocks will be essential, as replenishment of depleted populations from distant spawning adults becomes less likely.

At this time, the projections of how ocean currents are expected to change lack sufficient confidence and resolution, at scales relevant to the ecology of coastal fish and invertebrate species, to enable meaningful estimates of the likely impact on individual coastal fisheries species[36,37]. Also, little is known about the present levels of connectivity within meta-populations among reefs, islands and nations for any of the target species in the tropical Pacific. However, vertical stratification of the water column and associated declines in the delivery of nutrients to surface waters are likely to cause a general decline in productivity of coastal marine assemblages. Declining nutrient availability imposes fundamental limitations on available energy and productivity. Although some changes in community structure and energy dynamics within coastal ecosystems may occur, the adaptive capacity to withstand a fall in nutrient availability is limited. Nutrient limitation may also compound the increased metabolic demands of marine organisms coping with higher SST and reduced pH and lead to a significant decline in biological production.

Vulnerability

The productivity of all coastal fisheries is expected to be vulnerable to changes in the delivery of nutrients to coastal habitats, which are generally expected to decrease in the tropical Pacific as a result of weakening of the SEC and SECC, and increases in stratification of the water column. Local increases in productivity may occur in some locations, however, as currents change in velocity and direction (Chapter 3), and as freshwater runoff increases around high islands due to the projected higher rainfall intensity in the tropics (Chapter 2). In general, the stocks of predatory demersal fish, and the large nearshore pelagic fish that depend on the food chains supported by nutrient-rich waters[198], are expected to be negatively affected as the occurrence and intensity of the vertical mixing of the water column decline.

Any changes in the supply and settlement of larvae caused by changing currents and eddies are likely to have major effects on coastal fish and invertebrates. Locations that consistently receive a disproportionate number of settlers (recruitment 'hotspots') may be very important in supplying recruits to surrounding locations. Vulnerability to changing hydrodynamics is likely, therefore, to be localised. The capacity to downscale changes in ocean circulation to project these effects is presently limited. At the scales of islands and reefs, the weakening of the SEC and SECC is likely to reduce both the transport of pelagic larvae among distant islands and reefs, as well as the retention and accumulation of larvae within eddies formed adjacent to islands and reefs by currents.

9.3.2 Vulnerability to the indirect effects of climate change

Coastal habitats are particularly susceptible to a wide range of natural and anthropogenic disturbances[22,76]. The diversity, frequency and intensity of the anthropogenic influences on coastal habitats have been increasing worldwide over the past 100 years, leading to strong shifts in the structure of coral reefs[18,19], seagrass meadows[199,200] and mangroves[201–203]. Although the causes and the extent of coral loss vary regionally, mean coral cover throughout the Indo-Pacific decreased from 42.5% in the early 1980s to 22.1% in 2003[20]. Climate change threatens to compound the natural and direct anthropogenic disturbances, accelerating the degradation and loss of coral reefs (Chapter 5). Similarly, 35% of the global area of mangrove forests has disappeared since 1980, mostly due to intensified use and destruction[203]. These losses are also expected to be exacerbated by climate change, especially sea-level rise (Chapter 6). These structurally complex, yet highly vulnerable, coastal habitats are fundamental to sustaining coastal fisheries through their roles as nursery, feeding and shelter areas[83,204,205]. Climate-induced degradation of these habitats also poses a major threat to the great marine biodiversity of the tropical Pacific.

Exposure and sensitivity

The fish and invertebrates associated with coral reefs, seagrasses and mangroves are exposed to great changes in the quality and extent of the habitats that support them, due to climate change[27,104,206–208] (Chapters 5 and 6).

Based on the rate of coral loss reported over the last 20 years[20], and the projected effects of more frequent coral bleaching and ocean acidification, average coral cover throughout the Pacific is expected to decline to 15% by 2035. Moreover, coral reefs will become increasingly dominated by relatively robust coral genera (e.g. *Porites* and *Favia*), rather than the branching coral species (*Acropora* and *Stylophora*) prevalent today. By 2100 under the B1 emissions scenario, coral cover is likely to decrease to < 5% with weak management, and to < 2% under the A2 scenario (Chapter 5).

Extensive death of corals leads to profound changes in the biological and physical structure of reef habitats (**Figure 9.15**) (Chapter 5). Over time, coral skeletons of dead branching corals (e.g. *Acropora* and *Pocillopora*) break down into coral rubble[97,209], and the more robust skeletons of massive corals (e.g. *Porites*) become dislodged or gradually eroded *in situ*[209]. These processes contribute to long-term declines in structural complexity, and ultimately result in low-profile reef landscapes[209,210]. The bioeroding algae, which contribute to physical collapse of dead coral skeletons, also grow faster under elevated CO_2 conditions[211], further contributing to degradation of coral reefs with ongoing climate change.

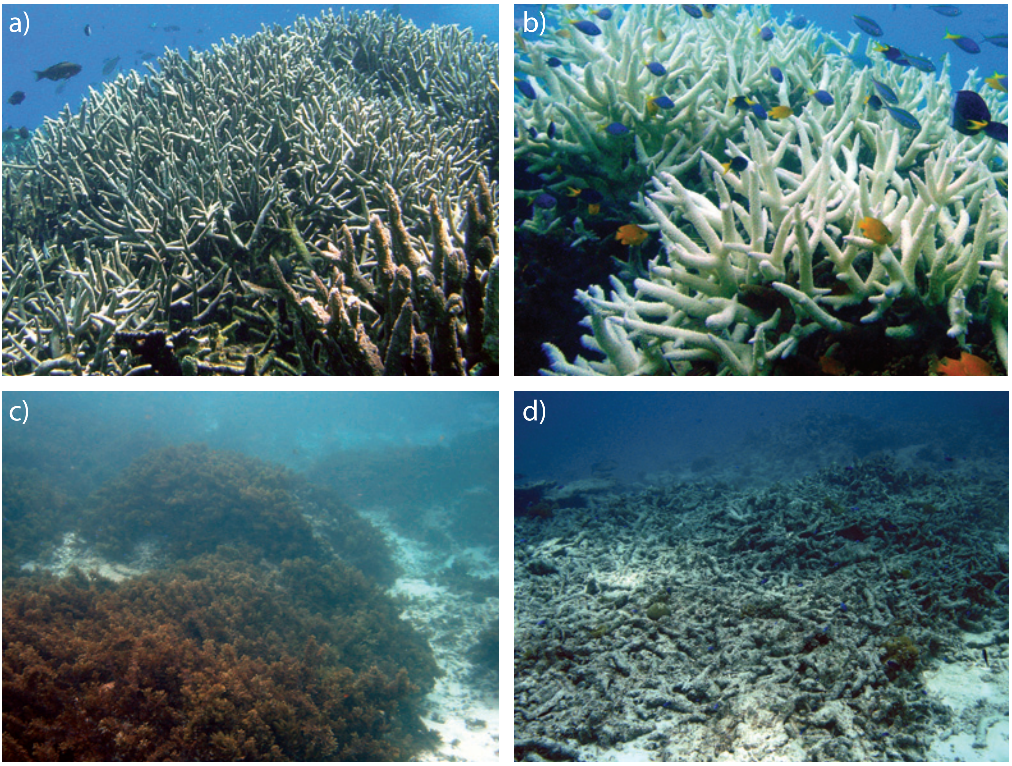


Figure 9.15 Changes in the state of coral reef ecosystems caused by climate-induced coral bleaching. Coral-dominated and structurally complex coral reef habitats (a) once bleached (b) can become overgrown with algae (c) and then collapse to form rubble banks (d) [Photos: Morgan Pratchett (a); Darren Coker (b); Shaun Wilson (c and d)].

In some instances, coral reef habitats become dominated by macroalgae[78] or other sessile fauna[212], fundamentally altering the nature of these ecosystems. Macroalgae are expected to proliferate on reefs under climate change for the following reasons (1) the reduced abundance of corals increases space for colonisation of algae; (2) the lack of physical structure (formerly provided by reef-building corals) leads to declines in abundance of herbivorous fish that typically control the growth of macroalgae; and (3) increasing temperatures and higher rainfall/runoff will favour the growth and productivity of macroalgae. The onset of such degradation is expected to occur even earlier in places where overfishing has already reduced the abundance and diversity of herbivores[18,19,77].

As mentioned above, the demise of coral reefs is not the only way in which coastal fisheries are exposed to degradation and loss of habitat. Depending on the location of PICTs, projected increases in water temperature, sea level, cyclone intensity and turbidity of coastal waters caused by higher rainfall, can be expected to affect the growth and survival of mangroves, seagrasses, non-reefal algal habitats, and the nature of intertidal flats. While data are scarce on recent and projected effects of climate change within non-reefal habitats of the tropical Pacific, data from elsewhere (e.g. Australia) indicate the likelihood of major effects[35]. The response of mangroves to such impacts is typically manifested as a change in their zonation, structure and species composition (Chapter 6). Similarly, for seagrasses, changes in local patterns of abundance and species composition are likely, but reductions in the overall extent of seagrass habitats may or may not occur (Chapter 6).

The fish and invertebrates that depend on coral reefs for food and/or shelter are highly sensitive to degradation and loss of these important habitats[213–215]. The frameworks provided by living and intact corals are also important for sustaining a great diversity and abundance of species that do not feed or live on corals directly[216–218]. As habitat diversity and topographic complexity decline, there are fewer places for reef-associated species to shelter from potential predators or competitors[219,220], with the result that degraded reef environments support fewer individuals and fewer species[76,97,210,218] (**Figure 9.16**). Loss of habitat complexity is especially detrimental for small-bodied fish (including both small species and juvenile phases of larger-bodied species) because such individuals are more exposed to predatory fish associated with coral reef environments[221].

The projected decline in abundance of juvenile stages of fishery target species due to degradation and loss of coral reefs is of particular concern. Small to medium size classes (up to 30 cm total length) of target species can decline substantially after the collapse of the reef structure, which is likely to lead to failure of recruitment to adult stocks, and declines in fisheries catch[222]. These declines have been profound for herbivorous fish stocks, for example parrotfish, and a decline in medium size classes of piscivorous species can result due to the absence of their prey[222]. An estimated 56%

of fisheries species targeted by subsistence fisheries in PNG are strongly associated with coral reefs[9] and likely to be affected by degradation or loss of coral-dominated habitats.

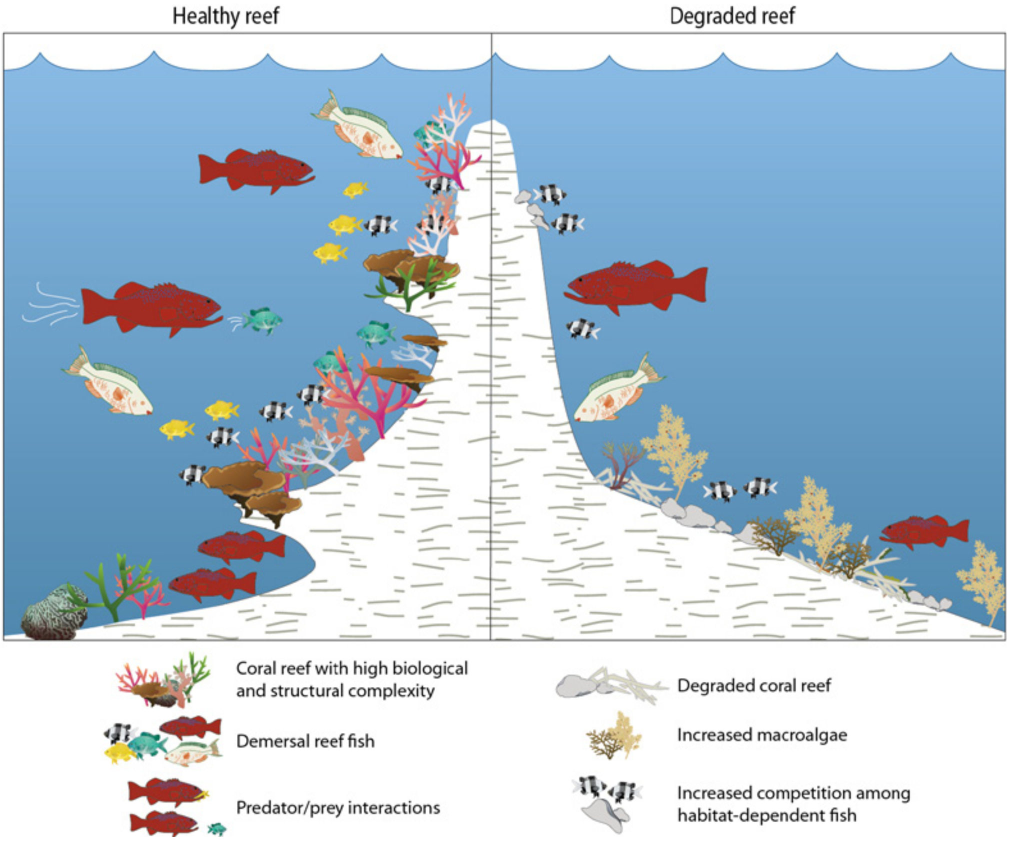


Figure 9.16 Degradation of coral reef habitats (declines in live coral cover and loss of structural complexity) has implications for the abundance and diversity of reef-associated fish and invertebrates. Prey are expected to decline in abundance due to lack of suitable habitat, ultimately leading to declines in abundance of predatory fish. Generalist benthic feeding fish (e.g. herbivores) may have access to more food on degraded reefs because of the increase in macroalgae, and become more abundant. However, the projected changes in habitat structure, and the expected alterations in sea surface temperature and oceanic currents, may simultaneously reduce recruitment success of such generalist species.

The role played by seagrasses, mangroves and intertidal flats in supporting fisheries production in the tropical Pacific is poorly understood. However, vegetated areas may provide important nurseries and feeding habitats for a wide range of coastal fish species[223–225]. Reduced coverage and structural complexity of the vegetated habitats caused by more severe disturbance from cyclones, increased stress from higher temperatures, reduced light levels from more turbid conditions and sea-level rise[226–229], can be expected to reduce recruitment success for many species of fish and invertebrates in the absence of other shelter[230]. Erosion of intertidal flats, and changes to the associated microalgae that drive the high productivity of these areas[224], are also likely to occur as a result of more intense cyclones and sea-level rise (Chapter 6). Such changes can be expected to alter the function and productivity of intertidal flats, which represent feeding areas for roving fish and are in themselves an important source of food for subsistence fishers (e.g. the fishery for arc shells in Kiribati).

Potential impact and adaptive capacity

The loss of the structural and biological complexity of coral reefs is expected to profoundly affect the types of fish and invertebrates associated with them. Species that depend on live coral for food, and on the variety of shelter created by structurally complex reefs for their survival, are likely to disappear[76,97,104]. These coral-dependent and highly specialist reef fish may be replaced by herbivorous and generalist species, leading to changes in community composition rather than net losses of biodiversity[231]. However, simplification of reef habitats will involve the loss of many existing energy pathways, making these ecosystems much more sensitive to future disturbances, including overfishing[232]. As such, effects of climate change on coastal fisheries associated with coral reefs may not be immediately apparent, but may result in slow, long-term (decadal) declines in yields as resilience and productivity are gradually eroded.

Increasing loss and degradation of non-reefal habitats (e.g. mangroves and seagrasses) will also affect coastal fisheries, though the effect this will have on overall fisheries production is not clear. It remains to be determined what proportion of target fisheries species are specifically reliant on mangrove and seagrass habitats, either as juveniles or throughout their life, and whether these fish can use alternative areas in the absence of preferred habitats. In the Caribbean, some coral reef fish (e.g. parrotfish) depend heavily on mangroves as nursery areas, and have become locally extinct where mangroves have been removed[84]. However, some fish that use mangroves as nurseries were able to use alternative habitat types, and were no less abundant on islands without mangroves[84]. Similar studies conducted in the tropical Pacific have revealed relatively little overlap in fish assemblages from coral reef habitats versus mangroves or seagrass beds[83,233], but some of the fish found in mangroves have important functional roles on coral reefs[83]. Widespread loss or degradation of non-reefal habitats is likely to lead to loss of some species, causing local declines in biodiversity, which may or may not affect overall fisheries production.

The extent to which species may be able to adapt to changes in resource availability and habitat structure depends on their ecological versatility. Highly specialised species, such as the coral feeding butterflyfish *Chaetodon trifascialis* are completely dependent on specific types of corals and will die without access to them[234,235]. On the other hand, other species of butterflyfish, such as *C. lunulatus*, are capable of switching their diets to feed on whatever coral prey is available[236]. Highly specialist species are, therefore, extremely vulnerable to habitat loss and degradation, and likely to become locally extinct if catastrophic changes in reef habitats occur[104,213], whereas more generalist species capable of using a range of prey and habitat types are likely to persist[231]. Thus, species vary along a continuum from highly specialised to highly generalist, with the most specialised species likely to be affected first and worst by environmental disturbances[113]. The extent to which other more generalist species are affected will depend upon the severity and extent of the habitat degradation and associated resource depletion.

Vulnerability

Reef-associated fish and invertebrates are likely to become less abundant following extensive degradation and loss of the coastal habitats on which they depend, especially coral reefs. The demersal fish commonly associated with coral reefs that are expected to be affected include emperors, snappers, groupers, surgeonfish, parrotfish and rabbitfish[9]. These fish currently account for 35–80% (by weight) of the estimated total catch of demersal fish in PICTs (**Table 9.2**).

If water temperatures increase by 3°C, and CO_2 exceeds 550 ppm, as projected under the A2 emissions scenario by 2100, coral cover and habitat complexity will be greatly reduced (Chapter 5). This is likely to result in substantial reductions in the abundance of 62–75% of coral reef species, and similar proportions of reef-associated fish and invertebrates[76,210,215,218], including many species presently caught by subsistence and artisanal fishers[9]. Some of these species could persist in areas with remnant coral growth, but these areas will be small and poorly connected and unlikely to support diverse assemblages of fish and invertebrates. There may also be some replacement of specialist reef-associated species with more generalist species (e.g. Mugilidae). However, the loss of coral reefs and other critical coastal habitats is expected to progressively reduce production of demersal fish throughout the tropical Pacific.

9.4 Vulnerability of the four categories of coastal fisheries

Vulnerability to the combined effects of changes in SST, the pH of the ocean, currents and habitats, is expected to differ among the four categories of coastal fisheries. The direct effects of altered atmospheric and oceanic conditions are likely to vary among the key species within each category due to differences in their ontogeny and physiology. The indirect effects due to changes in habitats are also expected to differ among the four categories because the key species depend on coral reefs and the other coastal habitats in different ways. Integrating the effects of climate change on coastal fisheries involves combining the vulnerability of all four categories of coastal fisheries to both the direct and indirect effects.

Here we provide preliminary estimates of how each coastal fisheries category may be expected to respond to the projected changes in the atmosphere and ocean, and the habitats that support them, under the B1 and A2 emissions scenarios by 2035 and 2100. These vulnerability estimates are based on our expert opinion of how the various types of species in each category might be affected by climate change.

9.4.1 Fisheries for demersal fish

The dominance of demersal fish in the catches of coastal fisheries (**Table 9.6**) means that any negative effects of climate change on these fish will lead to major declines in fisheries production and/or marked changes in the structure of coastal fisheries. The most immediate and apparent threat of climate change to demersal fish is the loss and degradation of critical coastal habitats, particularly coral reefs. The demersal fish likely to be affected first and most severely are the small, strongly coral-dependent species, such as butterflyfish, wrasses and damselfish[104], which are the basis of fisheries for aquarium specimens. However, many large reef-associated fish species could also become locally extinct given the extent of habitat loss and reef degradation projected to occur if SST increases by more than 2.0°C (Chapter 5).

Alternatively, there may be corresponding increases in abundance of highly generalist species (e.g. herbivores) that do not rely on live coral substrates[231,237–239]. Some studies have documented increases in the local abundance of herbivorous fish immediately after extensive coral bleaching, possibly due to the greater abundance of algae caused by coral loss[104]. On longer time-frames, however, most reef-associated fish are expected to be less abundant in habitats with low coral cover because negative effects associated with declines in the structural complexity of reef habitats (reduced settlement and survivorship of juvenile fish) will offset any advantage provided by increases in food availability[97,222].

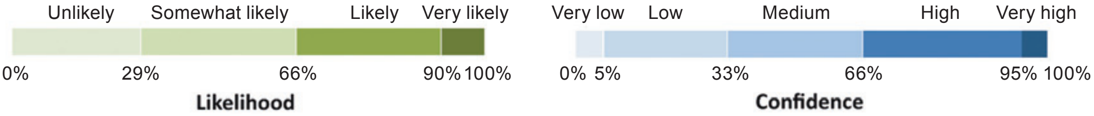
Consequently, overall declines in the abundance of demersal fish, and fisheries production, from coral reef habitats will be a combination of the responses of obligate, reef-associated and generalist species to the projected decreases in coral cover and structural complexity of coral reefs (Chapter 5 and Section 9.3.2). Major declines in species richness and the community structure of demersal fish are very likely, because of ongoing habitats loss and degradation of coastal habitats[76], but declines in fisheries production are likely to be minimal (restricted to a few strongly coral-dependent species) until 2035 (**Table 9.7**). Indeed, the vulnerability of demersal fish is expected to be low under the B1/A2 emissions scenarios in 2035 and any declines in production may be indiscernible against the backdrop of ongoing exploitation and habitat degradation. Very few locations in the Pacific are unaffected by human activities, which makes it difficult to isolate the effects of climate change[240].

By 2100 under the B1 scenario, increasing coral loss and associated degradation of coastal habitats are projected to affect a number of species. Coral reefs, for example, are expected to lose > 40% of their structural complexity, thereby reducing the number of reef-associated fish (individuals and species) that can be sustained by as much as 40%, and all demersal fish by 20%. Under A2 in 2100, coastal fish habitats are expected to be severely degraded (Chapters 5 and 6), leading to extensive loss of reef-associated and other habitat-dependent fish and a 20–50% reduction in all demersal fish (**Table 9.7**). Therefore, demersal fish are expected to have a moderate vulnerability to climate change under B1 in 2100 and a high vulnerability under A2 in 2100.

Projected declines in demersal fish by 2100 will result not only from the anticipated degradation of coral reefs, but also by progressive increases in recruitment limitation, due to decreases in strength of the SEC and SECC, and the effects of higher water temperatures on development and survival of fish larvae. Making projections about likely changes in recruitment is challenging, because of the complexity of the interacting factors that could be affected by climate change, but declines of up to 40% may possibly occur (based on the present inputs of larvae from distant sources). Such effects would lead to reduced and more localised replenishment of populations.

Table 9.7 Projected changes in productivity of the demersal fish component of coastal fisheries under low (B1) and high (A2) emissions scenarios in 2035 and 2100. The estimated responses of broad types of demersal fish are also shown. The likelihood of these responses (especially for A2 in 2100) is low to medium.

Type of species	Emissions scenarios		
	B1/A2 2035	**B1 2100**	**A2 2100**
Coral-dependent	-50%	-90%	-100%
Reef-associated	0%	-20 to -40%	-20 to -80%
Generalist	0%	0%	-10 to -20%
All demersal fish	**-2 to -5%**	**-20%**	**-20 to -50%**
	🟩 🟦	🟩 🟦	🟩 🟦



Alterations in the relative abundance of carnivorous and herbivorous fish, and changes in SST and the quality of coral reefs, have possible implications for the incidence of ciguatera fish poisoning in demersal fish, as well as the nearshore pelagic fish (e.g. Spanish mackerel and barracuda) that prey on them (Box 9.2). Chronic incidences of ciguatera are already limiting potential fish consumption in some parts of Cook Islands and French Polynesia[241], leading to significant decreases in the amount of fresh fish consumed. In the past, high incidences of ciguatera may have instigated the movement of Pacific settlements[242].

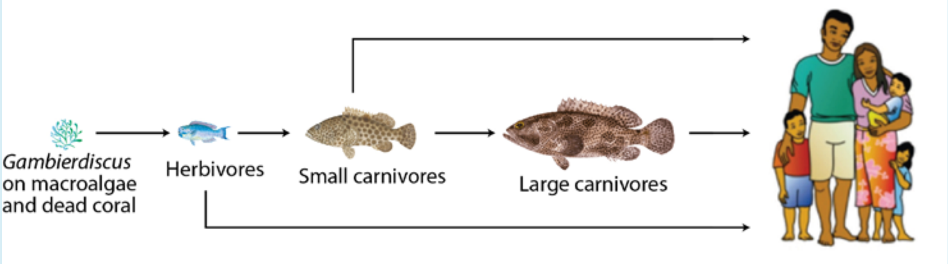
Data on the biology and ecology of fish associated with mangroves, seagrasses and intertidal flats are insufficient to assess additional consequences of declines in the quality and/or quantity of non-reefal habitats. For example, whether larval fish that settle in mangrove and seagrass habitats fail to do so successfully if the structure of these habitats is degraded or lost, or whether they will simply settle in other less optimal areas[84,230], is unknown. It is somewhat likely, however, that habitat loss and degradation of other coastal habitats will compound declines in fisheries production caused by expected changes in the structure of coral reef habitats. Changes in the

Box 9.2 Ciguatera fish poisoning

Ciguatera poisoning has been known for centuries in regions where people eat fish associated with coral reef environments – during his second expedition to the Pacific in the late 1790s, Captain Cook related how two red fish (possibly *Lutjanus bohar*) poisoned his officers. Ciguatera is the most common illness arising from eating fish, with 3400–4700 cases recorded from Pacific Island countries and Territories each year[263]. Because of inaccurate reporting, however, the records are considered to represent only 10–20% of the actual number of cases[264].

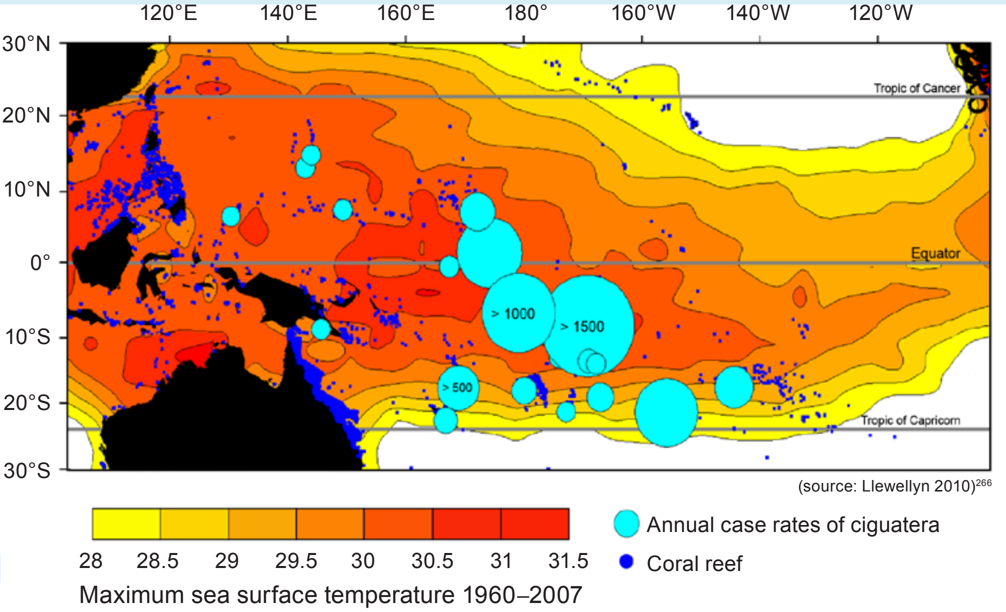
The organisms responsible for ciguatera fish poisoning are dinoflagellate microalgae in the genus *Gambierdiscus*. These microalgae live as epiphytes on the surface of macroalgae, or on dead coral, and are ingested by herbivorous fish when they graze the larger plants or substrate[263].

Gambierdiscus spp. produce toxins that are biotransformed into ciguatoxins by the fish that eat them[264]. The ciguatoxins reside in the muscle tissue of fish, and at much higher levels in the liver and viscera, and 'bioaccumulate' through the food chain. Consequently, the toxins may be found at highest concentrations in large or old carnivorous fish. Where *Gambierdiscus* bloom, however, herbivorous parrotfish and surgeonfish can also be poisonous[241]. Ciguatera-related toxins are resistant to cooking and freezing, so that people who eat ciguatoxic fish are exposed, regardless of how they prepare these fish.



It is difficult to tell whether a fish is ciguatoxic, but the symptoms of ciguatera, and the range of possible symptomatic remedies, are well known[246,263,264]. In general, the symptoms include numbness, tingling of the lips, tongue and throat, joint, muscle and abdominal pain, nausea, vomiting and severe diarrhoea. The classic symptom is the reversal of hot and cold sensations. The prognosis is usually benign, although severe cases of poisoning, which are the exception, can lead to paralysis, coma and even death.

Although this form of fish poisoning has been reported from coral reef habitats worldwide, both the incidence and toxicity of ciguatera are greatest in the Pacific. Within the region, ciguatera is more prevalent where corals have been damaged, allowing macroalgae to grow more profusely[263]. The disturbances to reefs that can promote ciguatera include rises in sea surface temperature (SST)[265]. Interestingly, ciguatera poisoning does not occur throughout the tropical Pacific, for example, it has not been observed in much of Solomon Islands, or in Pitcairn Islands – see map below showing relative abundance of ciguatera cases (blue circles) in the tropical and subtropical Pacific relative to maximum SST[266].



(source: Llewellyn 2010)[266]

Positive correlations have been observed between the annual incidence of fish poisoning and local increases in SST in PICTs that experience warming during El Niño conditions[267]. However, subsequent analysis indicates that any relationship between ciguatera and climate change needs to take account of more complex effects of temperature on the abundance of *Gambierdiscus*, the production of the toxin by the dinoflagellates, and the metabolism of the ciguatoxin by fish[266]. In particular, it appears that (1) SST needs to be above a lower threshold long enough to generate enough toxin in the ecosystem for ciguatera to be widely observed in a human population; and (2) if SST exceeds an upper limit long enough, occurrence of ciguatera decreases. Thus, increases in SST may have both a positive and negative effect on ciguatera case rates. If this hypothesis is correct, the zone in which ciguatera is prevalent may move poleward with climate change.

Regardless of the temperature range that favours ciguatera, the risk of higher incidences of this type of fish poisoning could increase in the future as a result of the projected degradation of coral reefs (Chapter 5). The consequence of such degradation is that, as corals die and macroalgae proliferate, reefs are likely to have more substrate for *Gambierdiscus*. Increases in ciguatera pose problems for many PICTs because both rural and urban communities depend heavily on fish associated with coral reefs for food[4].

strength and/or direction of major surface currents would also be expected to affect connectivity among different habitats, causing direct effects on recruitment by demersal fish that depend on links between habitats during ontogeny.

9.4.2 Fisheries for nearshore pelagic fish

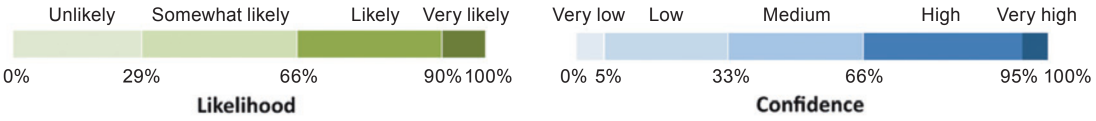
The potential to expand the catches of many of the small and large pelagic species involved in this fishery, particularly skipjack and yellowfin tuna, will be determined by changes to the production of the phytoplankton and zooplankton that underpin the food webs on which these species depend (Chapter 4). The wide-ranging nature of these species also means that they are likely to respond to future changes in environmental conditions by moving to more suitable regions and habitats[30,243] (Chapter 8).

Preliminary estimates of the future changes in the availability of nearshore pelagic species (**Table 9.8**) can be made by using the modelling for skipjack tuna (Chapter 8), and the projections of zooplankton production near the base of the food web (Chapter 4) that also supports the non-tuna species. When the large projected differences in abundance of tuna between the west and the east, and the greater projected decreases in productivity of zooplankton in the west (**Table 9.8**), are combined with the average proportions of tuna and non-tuna species in the catch, there are substantial differences in projected abundances of nearshore pelagic fish in the two parts of the region. In the west, the overall catch is projected to decrease by 2100, whereas it is likely to increase in the east by 15–20% in 2035 and 10–20% in 2100 (**Table 9.8**).

Table 9.8 Projected changes in productivity of the nearshore pelagic fish component of coastal fisheries for the eastern and western areas of the tropical Pacific region under low (B1) and high (A2) emissions scenarios in 2035 and 2100.

Type of species	West*			East**		
	B1/A2 2035	B1 2100	A2 2100	B1/A2 2035	B1 2100	A2 2100
Tuna[a]	+10%	0%	-20%	+35 to +40%	+40 to +45%	+25 to +30%
Non-tuna[b]	-4%	-10 to-15 %	-10 to -25%	-3%	-4%	-8%
Total[c]	**0%**	**-10%**	**-15 to -20%**	**+15 to +20%**	**+20%**	**+10%**
	🟩 🟦	🟩 🟦	🟩 🟦	🟩 🟦	🟩 🟦	🟩 🟦

* 15°N–20°S and 130°–170°E; ** 15°N–15°S and 170°E–150°W; a = approximations based on preliminary modelling for skipjack tuna (Chapter 8); b = approximations based on estimated average percentage change in the production of zooplankton in the Warm Pool, Archipelagic Deep Basins and North Pacific Tropical Gyre Provinces for the western part of the region; and for the Pacific Equatorial Divergence and South Pacific Subtropical Gyre Provinces in the east (Chapter 4); c = based on approximate weighted average for tuna and non-tuna species, where non-tuna species usually dominate the catch of nearshore pelagic fish from Pacific Island countries and territories (PICTs) in the west, and tuna and non-tuna species make approximately equal contributions on average to catches for PICTs in the east (derived from Table 9.6).



Overall, the nearshore pelagic fishery in the west is expected to have little vulnerability to climate change in 2035, a low to moderate vulnerability under B1 in 2100 and a moderate vulnerability under A2 in 2100. In the east, vulnerability is likely to be low because tuna are projected to be more abundant there under all scenarios (**Table 9.8**).

Notwithstanding the projected decreases in availability of nearshore pelagic fish in the west, all PICTs there should be in a position to substantially increase catches of tuna by nearshore pelagic fisheries in the years ahead because there should still be ample tuna for allocation to the coastal fishery (Chapter 8).

It is possible that the increased runoff from major rivers (Chapter 7) may increase the productivity of phytoplankton and zooplankton in coastal areas within the archipelagic waters of PNG, improving the environmental conditions for some species of small pelagic fish. However, we are not in a position to project the extent of potential increases in this component of the coastal fisheries catch.

9.4.3 Fisheries for targeted invertebrates

Climate change is expected to affect the targeted invertebrate species mainly through the loss and degradation of critical habitats (e.g. coral reefs, seagrasses and mangroves). In general, the greatest effects are likely to occur for highly specialist species with particular habitat requirements, e.g. the sea cucumbers *Holothuria fuscogilva* and *H. scabra*, which settle only in shallow seagrass meadows[244,245]. By 2035, the vulnerability of targeted invertebrates to climate change is expected to be low, with the projected changes to habitats estimated to result in a 2–5% decrease in production of the fishery. During the next 2–3 decades, however, overfishing will remain a much greater threat to stocks than climate change, especially for sea cucumbers[64,66]. Thereafter, depending on the extent to which fisheries management can prevent widespread over-exploitation, the effects of climate change may become apparent.

Continued degradation of the supporting habitats and increases in acidification of the ocean are likely to have significant effects on many target invertebrate species, with reduced calcification leading to higher rates of predation on juvenile molluscs. By 2100, vulnerability is expected to be low to moderate under B1 scenario, resulting in a 10% decrease in production. Under A2 in 2100, targeted invertebrate fisheries are likely to have a moderate vulnerability and a possible 20% decrease in production. The quality of many high-value invertebrates harvested for their shell (e.g. trochus, green snail and pearl oysters) is also expected to decrease progressively due to the projected increases in acidification of the ocean[153] (Chapter 11).

9.4.4 Fisheries for shallow subtidal and intertidal invertebrates

Climate change is expected to affect subtidal and intertidal habitats in several ways. First, projected increases in surface air temperatures (Chapter 2) will lead to marked increases in water temperatures in shallow environments. The higher temperatures are expected to reduce the number of species that can use intertidal areas. Second, the projected declines in pH and carbonate ion saturation are likely to affect growth and survival of bivalves (e.g. giant clams, arc and venus shells) and gastropods (e.g. trochus, turban and spider shells), which typically dominate catches from this fishery. Third, sea-level rise will reduce the area of the mangrove forests and intertidal flats (Chapter 6) favoured by some species, especially where land barriers constrain the shoreward migration of those habitats.

The extent to which these changes affect potential harvests requires estimates of the productivity of invertebrates from subtidal and intertidal habitats, which are unknown for the tropical Pacific. It is also very likely that there will be changes in abundance of different invertebrate species. Some species are expected to be favoured and others disadvantaged by the changing environmental conditions and alterations to the areas of mangrove, seagrass and intertidal flats. For example, predation on invertebrates by demersal fish would be expected to increase where intertidal areas become subtidal. Increased ocean acidification poses another grave risk to the potential production of the many molluscs that comprise this coastal fisheries category (**Figure 9.6**). Such effects are expected to be generally negative across these species.

Given the opportunistic nature of the species that underpin existing subtidal and intertidal invertebrate fisheries, the future potential production of this coastal fisheries category is very uncertain. Mainly on the basis of ocean acidification, we estimate that this fishery would have little or no vulnerability to climate change by 2035. By 2100, vulnerability could be low (a 5% decrease in production) under the B1 scenario, and low to moderate (a 10% decrease in production) under A2. These estimates would need to be revised considerably in the event of catastrophic sea-level rise, where sea level increases by up to 2 m by 2100 due to the breakup of the Greenland and West Antarctic ice sheets (Chapter 3), effectively drowning many highly productive intertidal habitats.

9.5 Integrated vulnerability assessment

Vulnerability of coastal fisheries in the tropical Pacific to climate change is expected to vary among PICTs, and be driven by a wide range of factors. These include the extent of the various coastal habitats, local biodiversity, the relative contributions of the four categories of coastal fisheries to the total catch, regional variation in projected changes to atmospheric and oceanic conditions and habitats, past levels of exploitation of stocks, and the extent of habitat degradation. Relative changes to atmospheric climate and features of the ocean are likely to be most pronounced in subtropical areas, although highest overall air temperatures and SST will be experienced in equatorial regions (Chapters 2 and 3). The consequences of local species extinctions are likely to be greatest for PICTs with naturally depauperate coastal fauna and flora[247], i.e. those in the southern and eastern parts of the tropical Pacific (Chapter 1). Fisheries for demersal fish and the two categories of invertebrate fisheries are expected to be more vulnerable in PICTs where stocks have been chronically overexploited, and where the supporting habitats have been severely degraded.

In this section, we summarise the projected changes to SST, ocean acidification, currents and habitats for the tropical Pacific under the B1 and A2 emissions scenarios in 2035, B1 in 2100 and A2 in 2100. We then integrate the projected changes in vulnerability and production for each coastal fisheries category, based on the relative contribution of each category to total catches (**Table 9.6**), to produce overall projected changes in total coastal fisheries production in 2035 and 2100 under B1 and A2.

9.5.1 Low and high emissions scenarios in 2035

Changes in environmental conditions in the tropical Pacific are expected to be fairly moderate until 2035 under both the B1 and A2 emissions scenarios (Chapters 2 and 3). By 2035, surface air temperatures are expected to be 0.5–1.0°C higher, increasing average SST in the tropical Pacific Ocean to 28.0°C whereas ocean pH is projected to decline by < 0.1 (Chapter 3) (**Table 9.9**). As described in Sections 9.3 and 9.4, the direct effects of these changes on all categories of coastal fisheries are likely to be fairly limited by 2035. Small increases in ocean temperatures of < 1°C may actually be beneficial for some key fish and invertebrate species, increasing reproductive success through more rapid development and increased survival of larvae[248].

The ongoing effects of climate-induced changes to nutrient supply (Chapter 4) and habitat degradation (Chapters 5 and 6) expected to occur by 2035 (**Table 9.9**) are likely to be more important. The projected declines in coral cover to around 15%, resulting in losses to the structural complexity of coral reefs (Chapter 5), and changes to mangroves and seagrasses are expected to reduce the diversity and abundance of demersal fish species progressively. Nevertheless, the dominance of coastal fisheries by demersal fish and nearshore pelagic species, some of which are likely to cope with the changes projected to occur by 2035, or even increase, means that reductions in total coastal fisheries production are expected to be negligible over the next two to three decades (**Table 9.10**).

When the projected vulnerability of all four categories of coastal fisheries are integrated, the overall vulnerability of coastal fisheries production is expected to be low in 2035 under the B1/A2 emissions scenarios across the region (**Table 9.10**).

Some variations in these overall conclusions are expected to occur, however. In the more eastern PICTs, the availability of nearshore pelagic fish is projected to increase (**Table 9.10**). In places where overfishing and/or anthropogenic habitat degradation (e.g. destructive fishing, sedimentation and pollution) have already reduced the diversity of key functional groups (e.g. herbivores), the effects of climate change may be more apparent by 2035 because the resources are expected to have greatly reduced resilience. In such places, effects of climate change in the coming decades may be indistinguishable from, and compounded by, the effects of increasing fishing pressure due to the rising local and global demand for fish.

Table 9.9 Projected changes to environmental conditions and habitats that underpin coastal fisheries for 2035 and 2100 under the low (B1) and high (A2) emissions scenarios. Information derived from Chapters 3–5.

Variable	Present	Emissions scenario		
		B1/A2 2035	B1 2100	A2 2100
Environmental Conditions				
Carbon dioxide (CO_2) (ppm)	> 380	> 400	500–600	750–800
Ocean				
Sea surface temperature (°C)	27.3	28.0	28.7	29.8
pH	8.1	7.9	7.9	< 7.7
Aragonite saturation	3.5–4.0	< 3.0	< 3.0	< 2.5
Surface currents				
- SEC (transport)	n/a	-3 to -5%	-9%	-18%
- SECC (strength)	n/a	-8 to -18%	-28%	-60%
Net primary production[a]	n/a	-4%	-8%	-13%
Habitats				
Coral cover (%)	30–40			
- Strong management		15–30	10–20	< 2
- Poor management		15	< 5	< 2
Dominant corals	Acroporidae	Poritidae, Faviidae	Poritidae, Faviidae	None
Reef structural complexity (% decrease)	n/a	20–30	> 50	> 90

a = Average for all five provinces listed in footnote to Table 9.8 (derived from Chapter 4); SEC = South Equatorial Current; SECC = South Equatorial Counter Current; n/a = non applicable.

At national levels, the 'health' of coral reefs and the productivity of the fisheries they support are broadly correlated with human population density[17,249,250] and the lack of alternative opportunities to earn income[43]. Well-designed monitoring programmes will be needed to separate the effects of climate changes on coastal fisheries from other stressors (Chapter 13).

9.5.2 Low emissions scenario in 2100

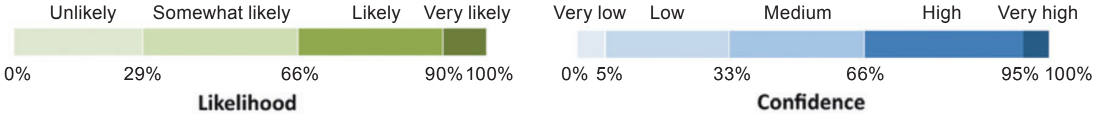
By 2100 under B1, surface air temperatures are expected to increase by 1.0–1.5°C (Chapter 2) and atmospheric concentrations of CO_2 are likely to exceed 500 ppm (**Table 9.9**). In the tropical Pacific, average SST is projected to increase by > 1.4°C to

28.7°C and pH will decline to ~ 7.9. These changes in SST and seawater chemistry are expected to have noticeable effects on the growth and survival of coastal fisheries species. In addition, major impacts on coastal fisheries production are expected to arise from projected loss and degradation of coral reefs, mangroves, seagrasses and intertidal flats (Chapters 5 and 6). Redistribution of species from equatorial to subtropical locations in response to the direct effects of climate change is also expected to occur – fish and invertebrate species not constrained to living on coral reefs or in other tropical coastal habitats are expected to move poleward, reducing

Table 9.10 Vulnerability (V) and projected changes in production (P) of the four categories of coastal fisheries and total coastal fisheries production in 2035 and 2100 for the B1 and A2 emissions scenarios. Note that the availability of nearshore pelagic fish is expected to increase in the eastern part of the region (Chapter 8). The main potential impacts of climate change projected to cause future variations in production of coastal fisheries are also summarised here.

Variable			**Coastal fisheries category**					**Total coastal fisheries*** **	
			Demersal fish	**Nearshore pelagic fish**		**Targeted invertebrates**	**Shallow subtidal and intertidal invertebrates**		
Present contribution to coastal fisheries production			56%	28%		2%	14%		
				West*	East**			West*	East**
Vulnerability and projected change in production	B1/A2 2035	**V**	L	nil	L	L	nil[a]	nil[a]	nil[a]
		P	-2 to -5%	nil	+15 to +20%	-2 to -5%	nil	Negligible	Negligible
			🟩 🟦	🟩 🟦	🟩 🟦	🟩 🟦	🟩 🟦	🟩 🟦	🟩 🟦
	B1 2100	**V**	M	L-M	L	L-M	L	M	L
		P	-20%	-10%	+20%	-10%	-5%	-10 to -20%	-5 to -10%
			🟩 🟦	🟩 🟦	🟩 🟦	🟩 🟦	🟩 🟦	🟩 🟦	🟩 🟦
	A2 2100	**V**	H	M	L	M	L-M	M-H	M
		P	-20 to -50%	-15 to -20%	+10%	-20%	-10%	-20 to -35%	-10 to -30%
			🟩 🟦	🟩 🟦	🟩 🟦	🟩 🟦	🟩 🟦	🟩 🟦	🟩 🟦
Major impacts			Habitat loss, and reduced recruitment due to ⇧SST and ⇩currents	Reduced production of zooplankton in food webs for non-tuna species and changes in distribution of tuna		Habitat degradation, and declines in aragonite saturation due to ocean acidification	Declines in aragonite saturation due to ocean acidification		

* 15°N–20°S and 130°–170°E; ** 15°N–15°S and 170°E–150°W; *** assumes that the proportions of the four coastal fisheries categories remain constant; a = nil or very low vulnerability; ⇧ = increasing sea surface temperature; ⇩ = reduced currents; L = low; M = moderate; H = high.



the abundance and diversity of fisheries species in equatorial regions. Independent analyses also project that, without any compensatory increases in growth and abundance of local species, the estimated redistribution of tropical fisheries species could contribute to declines in coastal fisheries production[147].

On coral reefs, increased temperatures and ocean acidification are expected to effectively eliminate branching corals and other sensitive habitat-forming species, thereby reducing coral cover to < 5% under poor management, which will reduce habitat complexity by > 50% (**Table 9.9**). Extensive coral depletion will have a disproportionate effect on many smaller, coral-dependent demersal reef fish (**Table 9.7**) not targeted by coastal fisheries[76,104] (except for aquarium fisheries). However, there are also likely to be knock-on effects for overall production of carnivorous reef-associated demersal fish (**Table 9.7**), caused by declines in the abundance of potential prey fish. When the effects of degradation of other coastal habitats are included, the abundance and diversity of all demersal fish in coastal habitats is expected to decrease by 20%[76] (**Table 9.10**).

The availability of nearshore pelagic fish is expected to decrease by 10% in the western part of the region, but increase by 20% in the east (**Table 9.8**). Targeted invertebrates and those gleaned from subtidal and intertidal areas are projected to decrease by 10% and 5%, respectively.

Taken together, declines in the local production of fish and invertebrates from critical coastal habitats, and movement of some generalist species, are somewhat likely to cause a decline in total coastal fisheries production of 10–20% in the west and 5–10% in the east (**Table 9.10**). The integrated vulnerability for all coastal fisheries is estimated to be moderate in the west and low in the east by 2100 under the B1 emissions scenario (**Table 9.10**). This assessment is based on the assumption that movement of demersal fish is likely to be highly constrained, even though the potential of corals to acclimatise and adapt to moderate long-term temperatures may increase[18] (Chapter 5).

9.5.3 High emissions scenario in 2100

Under the A2 emissions scenario, drastic changes in environmental conditions for the tropical Pacific are expected to occur by 2100 (**Table 9.9**). Surface air temperatures are projected to increase by up to 3.0°C and CO_2 concentrations are likely to be 750–800 ppm. These changes are expected to raise average SST to 29.8°C, reduce pH by 0.3–0.4 units and take aragonite saturation below 2.5. The major consequences are likely to be increased coral bleaching and declines in calcification by corals and coralline algae, molluscs and echinoderms (Chapter 5) (Section 9.4.3). This is expected to reduce habitat for demersal fish, food for nearshore pelagic fish, and the abundance of sea cucumbers, gastropods and bivalves that comprise the fisheries for targeted invertebrates and those gleaned for subsistence.

The drastic loss of structural and biological complexity of coral reefs, and their subsequent domination by macroalgae (Chapter 5) under this scenario, is likely to have profound effects on local abundance and diversity of fish and invertebrates associated with coral reefs. Production of demersal fish is expected to be severely affected. Indeed, heavy mortality of corals, and corresponding decline in habitat complexity, have been calculated to reduce coral reef fish abundance by up to 65%[97,210,218,251]. In addition, reduced oceanic transport associated with weakening of the SEC and SECC is expected to affect replenishment of demersal fish and decrease the supply of nutrients to coastal areas in the western Pacific (**Table 9.9**) (Chapter 4). Even among herbivorous fish, negative effects associated with declines in habitat structure and reduced replenishment could more than offset any benefit from increased availability of food resources (macroalgae).

The combination of these expected effects is likely to reduce the production of demersal fish by 20–50% under the A2 scenario by 2100 through strong effects on coral-dependent and reef-associated species (**Table 9.7**). A 15–20% reduction in the productivity of nearshore pelagic fish is also expected in the western Pacific, and a 10% increase in the east (**Table 9.8**). The productivity of targeted invertebrates is likely to decrease by 20% and those collected from shallow subtidal and intertidal areas by 10% (**Table 9.10**). Taken together, these changes are expected to reduce the overall production from coastal fisheries by 20–35% in the west and 10–30% in the east under the A2 scenario by 2100 (**Table 9.10**), with negative impacts likely to be apparent across most species, except the tuna taken by the nearshore pelagic fishery in PICTs in the east. Thus, the vulnerability of all coastal fisheries categories combined to climate change under the A2 scenario in 2100 is expected to be moderate to high in the west and moderate in the east (**Table 9.10**).

9.6 Uncertainty, gaps in knowledge and future research

The expected effects of climate change on the productivity of the four categories of coastal fisheries outlined above are surrounded by various levels of uncertainty (**Table 9.10**). While climate change is expected to have significant direct and indirect effects on coastal fisheries, our knowledge of such effects is extremely limited. For example, the effects of increasing temperature and declining pH on tropical marine fish have only been tested for relatively small and strongly site-attached species, mostly damselfish[143]. The extent to which these findings are relevant to important fisheries species (e.g. emperors, snappers, groupers, parrotfish, surgeonfish and rabbitfish) is unknown, which reduces the confidence with which we can project changes in coastal fisheries production due to expected alterations in environmental conditions and the structural complexity and biological diversity of supporting habitats.

Improving our understanding of the vulnerability of coastal fisheries to climate change, and identifying effective management actions, will depend to a large extent on doing the following research, outlined in Chapters 2 to 6.

- Obtaining high-quality observations of surface climate and oceanographic conditions throughout the tropical Pacific and identifying their links to coastal ecosystems.
- Downscaling the models for surface climate and oceanographic conditions to the scale of islands[ii] to allow more rigorous assessment of local sensitivity and vulnerability of coastal fish and invertebrates to changes in SST, nearshore currents and ocean acidification.
- Producing an inventory of vegetated coastal habitats, including mangroves and seagrasses, their connectivity to coral reefs, and their environmental thresholds for growth and survival.

Filling important gaps in knowledge also depends on the specific research on coastal fish and invertebrates listed below, so that we can understand better the likely responses of key species to changes in environmental conditions and habitats.

1. Assessing the role of coral reefs, and variation in their structural complexity and biological diversity, in moderating the distribution and abundance of reef-associated fish and invertebrate species harvested by commercial and subsistence fisheries, especially during larval settlement and recruitment. This research needs to be combined with studies of comparative resilience of different reef-building corals, to assess likely changes in composition and structure of reef habitats.
2. Improving our knowledge of the role of mangroves, seagrasses and intertidal flats in supporting the fish and invertebrates caught by coastal fisheries. In particular, we need to know how these habitats function as nursery and feeding areas, their links with coral reefs, and whether fish and invertebrates use the different habitats sequentially during ontogeny, or whether the configuration of the habitat mosaic affects the ecosystem services provided by mangroves, seagrasses and intertidal flats.
3. Testing the sensitivity and adaptive capacity of fish and invertebrate species important for existing and future fisheries production to the effects of rising SST and declining pH, including effects on early life history stages. This research should include (i) testing the combined effects of these variables and their interactions with other anthropogenic stressors, and (ii) assessing the ability of target fisheries species to adapt to these environmental changes.

[ii] This work is now being done 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

4. Determining whether there is a link between ciguatera fish poisoning, which can render demersal fish and some nearshore pelagic fish inedible, and climate change. In particular, research is needed to determine whether (i) populations of the microalgae *Gambierdiscus* spp., from which ciguatera originates, are affected by deterioration of coral reefs due to climate change; and (ii) projected changes in SST are likely to alter the areas in which ciguatera occurs, and its virulence.
5. Determining the risks to coastal fisheries, and the communities that rely on them for food, that climate change may alter the incidence of toxic marine algae other than *Gambierdiscus* spp.
6. Evaluating the likely effects of higher levels of nutrients from the projected increases in runoff around high islands in tropical Melanesia (Chapter 7) on the productivity of small pelagic fish species.
7. Assessing the vulnerability to climate change of deepwater species taken by coastal fisheries not considered in this chapter, especially snappers and groupers.

In addition, monitoring the size and composition of catches for all four categories of coastal fisheries must be established across the region. In particular, practical, well-designed sampling programmes are needed to (1) build up more reliable information on the contribution of the four categories of coastal fisheries to food security and livelihoods in each PICT, and the success of adaptations to retain the benefits of coastal fisheries, using household income and expenditure surveys[252]; (2) distinguish the catches for each category of coastal fisheries derived from different habitats; and (3) separate the effects of climate change from other impacts on coastal fisheries.

Photo: Joshua Cinner

Harvesting demersal fish, Papua New Guinea

9.7 Management implications and recommendations

Coastal fisheries have immense nutritional, social, cultural and economic value to the people of the Pacific[1,4,5,23,253] (Chapters 1 and 12). Improving the management of coastal fisheries to meet the needs and aspirations of growing populations is an imperative for PICTs, particularly given their heavy reliance on subsistence fisheries for food security, the limited opportunities to earn income in many rural areas, and a broad range of other drivers affecting the sector[25,26]. This challenge is made all the more demanding by the likely effects of climate change on the production of all four categories of coastal fisheries, but especially demersal fish.

Apart from urgent actions to keep atmospheric CO_2 concentrations below levels expected to damage coral reefs[254] (Chapter 5), a number of management recommendations can be made to optimise benefits from coastal fisheries in the face of ongoing changes to the climate. These measures centre on nurturing the habitats that support coastal fisheries, and avoiding overfishing, which is likely to make some species more sensitive to the effects of climate change[34]. Most of these measures have long been proposed for the toolbox for managing coastal fisheries in the Pacific[1,66,255], but now take on added importance to build resilience to climate change. These measures are outlined briefly below.

- Prohibit local activities that reduce the structural complexity and biological diversity of coral reefs, mangroves and seagrasses to assist these important coastal fisheries habitats to maximise their potential to adapt to climate change (Chapters 5 and 6). The high value of fish habitats needs to be emphasised in coastal zone management plans, and the principles of integrated coastal zone management[256,257] need to be applied. Such efforts will help avoid or minimise impacts from runoff of nutrients and sediments from land use in adjacent catchments, destructive fishing, coral extraction, removal of mangroves, dredging of seagrasses and pollution.
- Keep production of demersal fish and invertebrates within sustainable bounds by ensuring that sufficient spawning adults are safeguarded for regular replenishment of stocks. This constraint requires diagnosis of the internal and external factors affecting fishing by coastal communities, and the implementation of durable, practical and adaptive management to address these various drivers[24] (Chapter 13). Important management measures include (1) creating alternative livelihoods through development of enterprises outside the fisheries sector and through sustainable aquaculture to prevent fishing effort that cannot be supported by stocks[24,26]; (2) strengthening simple community-based management[255]; (3) implementing national fishery regulations (e.g. size limits, closed seasons and areas, gear restrictions and export bans) to underpin community-based management in a way that prevents overfishing; and (4) promoting awareness of the inter-dependence of fishing communities, based on the connectivity between habitats in the life cycles of target species and the need for all stakeholders to manage their resources cooperatively[258].

It is especially important to protect stocks against localised depletion to avoid the situation where replenishment of populations relies on sporadic recruitment from distant sources within a meta-population. Such replenishment is increasingly unlikely where increased SST and altered current patterns reduce the availability of juveniles derived from remote areas (Section 9.3.1.3).

- Raise awareness among fishing communities of the likely changes in species composition of demersal fish under climate change, for example, greater relative abundance of herbivorous fish. Assist communities to switch effort to these species and develop methods to harvest them within sustainable bounds, and in ways that do not adversely affect the important role played by herbivores on coral reefs.
- Rebuild populations of targeted invertebrate species to densities above the thresholds identified for regular replenishment, in order to restore the benefits of these resources on a sustained basis. Sea cucumber fisheries are particularly susceptible to recruitment overfishing[64,66,91]. Strict controls on the export of the smaller size classes and conservative management thresholds based on indicators should be established. Populations of trochus need to be restored in many areas to at least 500–600 individuals per ha, with a wide spread of size classes, before fishing is considered. Restricting future catches to 180 shells per ha per year, preferably with 3- to 5-year moratorium periods between fishing events, should then provide sustainable harvests[10].
- Diversify and increase fishing activities for nearshore pelagic fish through (1) use of low-cost, inshore anchored FADs to improve the catches of skipjack and yellowfin tuna by subsistence and small-scale commercial fishers; and (2) development of fisheries for small pelagic species (fusiliers, anchovies, mackerel, pilchards, sardines, scads and squid)[4,10]. Inshore, anchored FADs, in particular, promise to provide access to the greater quantities of fish that will be needed for food security by many PICTs as their human populations continue to grow (Chapter 12). However, care needs to be taken to position such FADs where they provide access to tuna, so that the FADs do not increase the fishing mortality of large nearshore pelagic species associated with coral reef habitats (e.g. Spanish mackerel).

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Appendix 9.1 Overview of the SPC PROCFish Project

The Pacific Regional Oceanic and Coastal Fisheries (PROCFish) Development Project was initiated in March 2002, and conducted by the Coastal Fisheries Programme and Oceanic Fisheries Programme at the Secretariat of the Pacific Community. The coastal component of PROCFish combined socio-economic surveys and local ecological assessments to gauge the importance and condition of reef and lagoon fisheries throughout the region. Research was undertaken at 4–5 sites in each of 17 Pacific Island countries and territories (PICTs) (**Table 9.1**). Sites represented distinct fishing grounds with active reef fisheries by a discrete human population (i.e. a relatively closed system of local exploitation). As such, the data from the PROCFish Project do not encompass the full range of variation within each PICT. Most importantly, relatively little information was collected close to large urban centres.

Socio-economic surveys were conducted at each site, using a 'snapshot approach'[268], involving analyses of 25 households and a corresponding number of people catching fish and invertebrates. Random sampling was used to provide an average and representative picture of fishing in each community, including people who do not fish, those engaged in fishing for fish and/or invertebrates for subsistence, and those engaged in fishing activities for livelihoods (income) on a small-scale, artisanal basis. The main aims of the household surveys were to (1) collect recent demographic information (needed to calculate seafood consumption); (2) determine the number of fishers per household by gender and type of fishing activity (needed to assess the total fishing impact of a community); and (3) assess the relative dependency of the community on coastal resources.

Ecological assessments were conducted separately for fish and invertebrates. Fish resources and associated habitats were sampled using distance-based underwater visual census (D-UVC). At each site, surveys were conducted along 24 transects, with six transects in each of the four main coral reef structures: sheltered coastal reefs, intermediate reefs, back-reefs and outer reefs. Only coral reef fish of interest for consumption or sale, and species that could potentially serve as indicators of coral reef health (e.g. butterflyfish), were surveyed. Low percentage occurrence could either be due to scarcity (which is of interest) or low detectability (representing a methodological bias). Therefore, analyses were restricted to the 15 most frequently observed families of fish for which D-UVC is an efficient resource assessment method. Substrate characteristics were recorded within ten, 5 m × 5 m quadrats located on each side of a 50 m transect ($n = 20$ quadrats per transect), using a standard method[269].

Various survey methods were used to compare the status of commonly targeted invertebrates across PICTs and the region. A general assessment of large sedentary invertebrates and habitats was made at spatial scales relevant to species (or species groups), using a tow-board technique[270]. Broad-scale surveys were used to record a range of invertebrates caught for subsistence across sites, whereas invertebrate species targeted by commercial fisheries for export were assessed using more detailed surveys of specific habitats. At each site, surveys were made at multiple 'stations'. At each station, epibenthic invertebrate resources, and some sea star and urchin species (potential indicators of habitat condition), were counted within six, 40 m × 1 m transects. Dedicated night searches were made for sea cucumbers at each station for predominantly nocturnal species. Sea cucumbers were also sampled by collecting all individuals present during three, 5-minute searches by two divers.

Appendix 9.2 Method used to estimate catches for the four categories of coastal fisheries

The following method was used to produce the estimates of catches for the four categories of coastal fisheries (demersal fish, nearshore pelagic fish, targeted invertebrates and subtidal and intertidal invertebrates) for each Pacific Island country and territory (PICT) in **Table 9.6** and Supplementary **Table 9.1** (www.spc.int/climate-change/fisheries/assessment/chapters/12-supp-tables.pdf).

Subsistence catches

Subsistence catches for demersal fish, nearshore pelagic fish, and subtidal and intertidal invertebrates were derived from the total coastal subsistence catches for each PICT in 2007, as reported by Gillett (2009)[5]. Expert opinion from national and regional fisheries agencies familiar with coastal subsistence fisheries in each PICT was used to estimate the average proportion of nearshore pelagic species (as defined in Section 9.2.1.2) in total national subsistence catches (see first data column in the table below). The total subsistence catch was then divided by this proportion to estimate the catch of nearshore pelagic species used for subsistence.

The remainder of the subsistence catch was assumed to be a combination of demersal fish and subtidal and intertidal invertebrates. To divide the remaining catch between these two categories, we used the proportions of fish and invertebrates recorded in the catches from coral reefs used by households for consumption from the SPC PROCFish Project socio-economic surveys at 4–5 sites in 17 PICTs (see third and fourth data columns in the table below). For those PICTs where surveys were not done, we used the average from other PICTs with communities of the same ethnic origin.

Commercial catches

The total catch of targeted invertebrates was derived from national records (or estimates) of exports for sea cucumbers (bêche-de-mer) and trochus for 2007, and anecdotal descriptions of catches for other species, such as mangrove crabs and spiny lobsters, and shrimp in the case of PNG, from Gillett (2009)[5], and occasionally expert opinion (e.g. for mangrove crabs in the case of New Caledonia).

When catches of targeted invertebrates occurred for a PICT, these were deducted from the total commercial catch. The remainder was then partitioned into the estimated proportion of nearshore pelagic fish in coastal commercial catches, based on the expert opinion of national and regional fisheries staff (see second data column in table below, and note that the estimated proportion of nearshore pelagic fish in total commercial fish catches differs from the proportion for subsistence fisheries in some PICTs). The remainder represented demersal fish.

Example for Fiji

In 2007, the total annual subsistence catch was estimated to be 17,400 tonnes[5]. The percentage of total subsistence catch comprised of nearshore pelagic fish was estimated to be 15% (2610 tonnes).

The reminder of the subsistence catch of 14,790 tonnes (17,400 tonnes - 2610 tonnes) was comprised of 76% (11,240 tonnes) demersal fish and 24% (3550 tonnes) subtidal and intertidal invertebrates.

PICT	**% nearshore pelagic fish**		**% demersal fish in remainder subsistence catch**	**% subtidal and intertidal invertebrates in remainder subsistence catch**	**Source of estimate for nearshore pelagic fish**
	Subsistence	**Commercial**			
Melanesia					
Fiji	15	30	76	24	A Vunesia, SPC
New Caledonia	10	20	58	42	J Bell, SPC
PNG	40	40	66	34	J Manieva, SPC
Solomon Islands	30	30	76	24	C Oengpepa, WorldFish
Vanuatu	20	35	64	36	L Chapman, SPC
Micronesia					
FSM	25*	40**	63	37	* Gillett (2009)[5]; ** A Vunisea, SPC
Guam	67	67	82[a]	18[a]	'Dominate' commercial landings, Gillett (2009)[5]
Kiribati	20**	22***	88	12	** A Vunisea, SPC; *** 1500 tonnes, Gillett (2009)[5]
Marshall Islands	25*	40**	88	12	* Gillett (2009)[5]; ** A Vunisea, SPC
Nauru	50	50	95	5	T Adams, Nauru Fisheries
CNMI	20	50	82[a]	18[a]	L Chapman, SPC
Palau	35	40	56	44	A Vunisea, SPC
Polynesia					
American Samoa	30	30	81[b]	19[b]	Gillett (2009)[5]
Cook Islands	60	60	87	13	I Bertram, SPC
French Polynesia	9	58	80	20	2332 tonnes commercial catch, Gillett (2009)[5]
Niue	50	50	81[b]	19[b]	Gillett (2009)[5]
Pitcairn Islands	15	n/a	81[b]	19[b]	Gillett (2009)[5]
Samoa	20	40	54	46	A Vunisea, SPC
Tokelau	40	n/a	81[b]	19[b]	K Passfield, IUCN; A Vunisea, SPC
Tonga	10	10	76	24	L Chapman, SPC
Tuvalu	25	35	93	7	A Vunisea, SPC
Wallis and Futuna	10	10	84	16	L Chapman, SPC

a = Average for surveys in Micronesia; b = average for surveys in Polynesia; n/a = not applicable.

National records show that the total catch of targeted invertebrates was 630 tonnes. When the catch of targeted invertebrates is deducted from the total commercial catch of 9500 tonnes[5], the remainder of the commercial catch was 8870 tonnes. This remainder is comprised only of nearshore pelagic fish and demersal fish because subtidal and intertidal invertebrates are used for subsistence. Nearshore pelagic fish comprised 30% (2260 tonnes) of the remainder and the rest (6210 tonnes) was demersal fish.

Sources of error

Considerable caution is needed in interpreting these estimated catches. The estimates are provided as a first attempt to quantify the relative importance of the four categories of coastal fisheries, and will need to be amended as more thorough methods are developed by PICTs to measure the catches within these categories of coastal fisheries. It is particularly important to note that:

- any errors in the catch estimates assembled by Gillett (2009)[5] are transferred here;
- estimates of the proportions of nearshore pelagic fish are seldom based on national catch records and represent expert opinion for most PICTs;
- the socio-economic surveys by the SPC PROCFish Project may not represent national trends, particularly in the larger PICTs, because they were conducted at only 4–5 sites and were targeted at coastal communities heavily engaged in fishing;
- the weights of invertebrates recorded in the SPC PROCFish Project socio-economic surveys represent whole animal weights but for several species the amount eaten is often a minor proportion of total weight; and
- the total catch of targeted invertebrates was often dominated by exports of bêche-de-mer, which usually represent < 10% of the live weight of sea cucumbers. Thus, the relative importance of targeted invertebrate catches is grossly underestimated.