Photo: Ben Ponia

Chapter 11

Vulnerability of aquaculture in the tropical Pacific to climate change

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'Pacific Islands have many attributes that favour the development of aquaculture.' (Adams et al. 2001)[i]

i Adams et al. (2001) Current status of aquaculture in the Pacific Islands. In: RP Subasinghe, P Bueno, MJ Phillips, C Hough, SE McGladdery and JR Arthur (eds) *Aquaculture in the Third Millennium. Technical Proceedings of the Conference on Aquaculture in the Third Millennium, Bangkok, Thailand, 20–25 February 2000*. Network of Aquaculture Centres in Asia-Pacific, Bangkok, Thailand, and Food and Agriculture Organization of the United Nations, Rome, Italy, pp. 295–305.

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11.1 Introduction

In addition to supporting a diverse range of fisheries, several of the coastal, freshwater and estuarine habitats in the tropical Pacific described in Chapters 5–7, and the species of fish and invertebrates they support (Chapters 9 and 10), are used for aquaculture. These activities all involve farming aquatic organisms, by intervening in the processes of reproduction and/or rearing to enhance production. They also involve individual or corporate ownership of the cultivated stock[1].

The rapid growth of freshwater and coastal aquaculture worldwide[2] has helped Pacific Island countries and territories (PICTs) to recognise that this type of farming is an important way of fostering economic development, food security and sustainable livelihoods for current and future generations[ii]. In particular, there is greater awareness that freshwater pond aquaculture can help supply the nutritious food needed by the growing populations of the region[3–5]. When planned well, this simple form of aquaculture has helped reduce poverty in Asia[6] and represents a promising way of providing fresh fish for the large inland populations of Papua New Guinea (PNG)[7]. Pond aquaculture enterprises in peri-urban areas also have potential to supply fish at a reasonable cost for the rapidly increasing urban populations of Melanesia, where poverty is increasing because of the growing number of people who no longer have access to land to produce food[8,9]. Rural communities have also identified aquaculture as a potential source of income to meet essential needs, and as a supplement or alternative to revenues from coastal and freshwater fisheries[10].

Nevertheless, development of aquaculture in the region has been limited compared with other areas of the world, partly because the governments of many PICTs lack a strategic framework for the sector. Policies, legislation and strategic planning to overcome technical, logistical and socio-economic constraints typical of aquaculture activities in the region[11,12] have often not been addressed adequately[13]. Such failures by government or the private sector[11,14] have been attributed to poor economic and financial planning, which has led to non-profitable investments or reliance on subsidies from governments or donors[13,15].

The exceptions are French Polynesia, New Caledonia and PNG (**Table 11.1**). In French Polynesia, the value of cultured black pearls was USD 173 million in 2007[24]. Pearl farming in French Polynesia employs 5000 people and represents 66% of the combined value of fisheries and aquaculture production[24]. Due to the large size of the economy, however, the value-added from pearl farming contributed < 1% to gross domestic product (GDP)[15]. In New Caledonia, shrimp farming was valued at USD 29 million in 2007[24] and contributed 33% to the combined value of production from fisheries and aquaculture[15]. Like French Polynesia, however, the value-added from fisheries and aquaculture is also < 1% of GDP.

ii Pacific Islands Forum, Vava'u Declaration, Forum Communiqué, Thirty-eighth Pacific Islands Forum, Nuku'alofa, Tonga, 16–17 October 2007. Annex B: The Vava'u Declaration on Pacific Fisheries Resources: 'Our Fish, Our Future'.

Despite the various constraints associated with aquaculture in the region, a wide range of aquaculture activities are currently underway in 16 of 22 PICTs (**Figure 11.1**, **Table 11.2**). In general, aquaculture activities in the tropical Pacific intended to produce commodities for food security are focused on freshwater habitats, whereas those developed to provide livelihoods are concentrated in coastal waters (**Table 11.2**). The number of households involved in growing freshwater fish for food security in the region is now thought to exceed those involved in culturing products intended for sale (**Table 11.3**). This is due mainly to the spread of small-scale freshwater aquaculture in PNG, where a conservatively estimated 10,000 (and possibly up to 50,000) small ponds have been constructed[7,iii].

Table 11.1 The production and value of aquaculture from Pacific Island countries and territories (PICTs) in 2007 (source: Ponia 2010)[24].

PICT	Production (tonnes)	Value (USD million)
French Polynesia	2464[a]	173
New Caledonia	1843	29
Others	993	8
Total	**5300**	**210**

a = Production comprised of 12 tonnes of black pearls with the remainder being mainly mother-of-pearl shell.

The recent regional Aquaculture Development Plan[10], and a series of national aquaculture development plans[16–21], promise to put aquaculture in PICTs on a new footing. However, the aspirations to develop both freshwater and coastal aquaculture in the region may be affected by the changes to surface climate and many of the features of the tropical Pacific Ocean described in Chapters 2 and 3. Because some forms of aquaculture rely on the collection of wild juveniles for grow-out, they may also be influenced by changes in the abundance of fish and invertebrates associated with coral reefs, seagrasses and mangroves (Chapter 9), and freshwater and estuarine habitats (Chapter 10).

In this chapter, we assess the vulnerability of aquaculture in the tropical Pacific to climate change. We begin by summarising recent and potential aquaculture production to set the scene for the sector, and then use the framework outlined in Chapter 1, based on exposure, sensitivity, potential impact and adaptive capacity, to evaluate the vulnerability of the main commodities for food security and livelihoods listed in **Table 11.2**. We also look at the risks posed by climate change to increased incidence of diseases. We then integrate all projected effects of climate change to assess the vulnerability of the sector as a whole. We conclude by examining the remaining uncertainty and the research needed to fill the gaps, and by identifying the management measures required to capitalise on the opportunities, and to minimise the adverse effects, expected to result from climate change.

iii Personal communication, Peter Minimulu, National Fisheries Authority, Papua New Guinea.

In assessing the vulnerability of aquaculture to climate change, we have not focused simply on existing activities and locations, but also considered the plans to expand the production of aquaculture in the region.

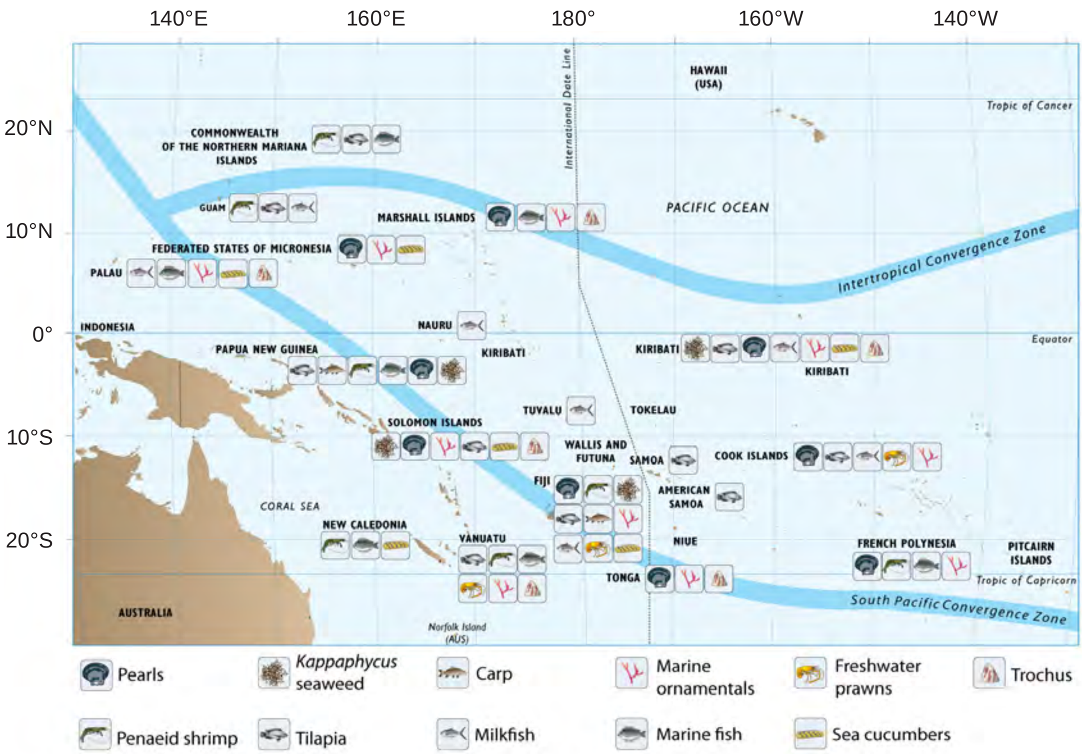


Figure 11.1 The main aquaculture activities underway in Pacific Island countries and territories.

11.2 Recent and potential aquaculture production

11.2.1 Commodities for food security

Pond aquaculture has been identified as a strategy to help meet two of the shortfalls in the fish needed for food security in PICTs. The first involves the very low rates of fish consumption among the large inland communities in PNG, where more people live than in the other 21 PICTs combined[4]. The second is the need to address the emerging gap in supply of fish for food security among urban and coastal communities in several PICTs, particularly in Melanesia, as population growth reduces the availability of fish per person below the levels recommended for good nutrition[3,4] (Chapters 1 and 12). The species of fish most likely to be produced efficiently in ponds to provide the commodities needed for food security, and the recent and potential production of these species in the region, are described below.

Table 11.2 The main aquaculture commodities produced to improve food security and create livelihoods in Pacific Island countries and territories (PICTs), together with the culture system(s) used to produce them, the environment(s) where they are grown, and the PICTs in which each aquaculture activity is established or under investigation.

Commodity	Culture system(s)	Environment(s)	PICTs involved*
Food security			
Tilapia	Earthen ponds	Terrestrial	American Samoa, Cook Islands, Fiji, Guam, Kiribati, CNMI, PNG, Samoa, Solomon Islands, Vanuatu
Carp	Earthen ponds, river releases	Terrestrial	Fiji, PNG
Milkfish	Earthen ponds, stone-walled sea pens	Terrestrial, shallow lagoons	Cook Islands, Fiji, Guam, Kiribati, Nauru, Palau, Tuvalu
Livelihoods			
Pearls	Submerged or surface longlines	Deep lagoons, sheltered bays	Cook Islands, Fiji, French Polynesia, FSM, Kiribati, Marshall Islands, PNG, Solomon Islands, Tonga
Shrimp	Earthen ponds, cement tanks	Terrestrial, adjacent to brackish or marine water source	French Polynesia, Fiji, Guam, New Caledonia, CNMI, PNG, Vanuatu
Seaweed	Off-bottom longlines, floating longlines	Shallow sandy back-reef areas of lagoons	Fiji, Kiribati, PNG, Solomon Islands
Marine ornamentals**	Seabed racks, floating cages	Lagoons	Cook Islands, Fiji, French Polynesia, FSM, Kiribati, Marshall Islands, Palau, Solomon Islands, Tonga, Vanuatu
Freshwater prawns	Earthen ponds	Terrestrial	Cook Islands, Fiji, Vanuatu
Marine fish	Floating sea cages, land-based raceways	Lagoons, sheltered bays	French Polynesia, New Caledonia, Palau, Marshall Islands, CNMI, PNG, Vanuatu
Sea cucumber	Released in the wild, pen grow-out, pond grow-out	Seagrass beds	Fiji, FSM, Kiribati, New Caledonia, Palau, Solomon Islands
Trochus	Land-based tanks, released in the wild	Coral reefs	Kiribati, Marshall Islands, Palau, Solomon Islands, Tonga, Vanuatu

* Includes past activities; ** includes giant clams propagated in hatcheries, fragments of wild corals and 'live rock', and collection of wild postlarvae.

11.2.1.1 Tilapia and carp

Mozambique tilapia *Oreochromis mossambicus* has become widely established in the region as a result of the intentional introduction of the species into lowland freshwater habitats in the 1950s and 1960s (Chapter 10) to increase the supply of fish for food[22,23].

Although it is now readily available in many PICTs, Mozambique tilapia has little potential for aquaculture because of its propensity for uncontrolled breeding, overcrowding and stunting[25,26]. More recently, some countries have introduced Nile tilapia *Oreochromis niloticus* to grow in ponds because of its suitability for aquaculture and its popularity as a food fish[27–29]. The particular attributes of Nile tilapia for farming are its adaptability to a wide variety of pond conditions, ease of reproduction, fast growth, lack of major diseases in semi-intensive production systems, tolerance to live transport to markets, availability of selectively-bred varieties, good market demand, and potential for export in value-added forms to Pacific-rim markets[25,30,32]. In addition, Nile tilapia is amenable to a variety of production systems, from extensive culture in small household ponds for subsistence to intensive industrial farms supplying urban markets[30,31].

Table 11.3 The estimated number of aquaculture farms dedicated mainly to producing commodities for food security (F) and livelihoods (L) in Pacific Island countries and territories (PICTs), and the number of people involved on a full-time, part-time or self-employed basis. Information covers the period 2007–2010 (source: SPC Division of Fisheries, Aquaculture and Marine Environment; Ponia 2010)[24].

PICT	Farming units			People employed		
	F	L	Total	F	L	Total
Melanesia						
Fiji	150	200	35 0	300	250	550
New Caledonia	-	40	40	-	560	560
PNG	> 10,000*	> 60	> 10,000*	> 10,000*	> 60	> 10,000*
Solomon Islands	8	353	361	10	600	610
Vanuatu	-	21	21	-	30	30
Micronesia						
FSM	-	5	5	-	20	20
Guam	-	5	5	-	20	20
Kiribati	1	1	2	5	5	10
Marshall Islands	-	1	1	-	5	5
CNMI	-	9	9	-	12	12
Palau	-	1	1	-	5	5
Polynesia						
American Samoa	-	11	11	-	15	15
Cook Islands	-	80	80	-	450	450
French Polynesia	-	530	530	-	5000	5000
Samoa	-	8	8	-	16	16
Tonga	10	5	15	10	10	20
Total	**13,169**	**1330**	**14,439**	**13,325**	**7058**	**20,323**

* Estimate provided by the National Fisheries Authority, Papua New Guinea, for the number of households involved in small-pond farming activities in inland areas in 2010; - indicates no aquaculture activity.

Nile tilapia is already becoming an aquaculture commodity that is helping to ensure food security in Fiji and PNG. In Fiji, the number of active household-level farms fluctuates between ~ 100 and 500, depending on the availability of inputs, such as fingerlings and feeds, and production is up to 300 tonnes per year. Although most of these farms produce for subsistence or local sales, some farmers produce several tonnes of fish per week for sale live at municipal markets. PNG apparently had an order of magnitude more small-scale tilapia farmers than Fiji[7] in 2007, with more recent estimates indicating that > 10,000 households are now engaged in small pond aquaculture in PNG (**Table 11.3**). However, because most farms in PNG are in remote highland locations, and also produce fish mainly for subsistence, collecting accurate production figures is difficult.

Demand for tilapia is growing in several PICTs due to shortages of coastal fish (Chapter 9). For example, a commercial tilapia farm in Vanuatu has no trouble selling its annual production of 80 tonnes at the central market in Vila, especially when rough seas reduce the supply of reef fish. The preference of people in the Pacific for whole fish of 200 to 400 g (plate size) increases the appeal of tilapia farming because the fish can be harvested after a relatively short (5–7 months) grow-out period.

The potential benefits of Nile tilapia for meeting the projected demand for fish for food security[4] need to be balanced with possible effects on biodiversity[5,33]. In combination with adverse effects on rivers of land degradation caused by agriculture and forestry (Chapter 7), Mozambique tilapia (commonly regarded as more invasive and ecologically damaging than Nile tilapia) may have contributed to the local loss of some native freshwater fish, such as gobies and gudgeons traditionally eaten in Fiji[34]. Feral Mozambique tilapia have reportedly been regarded as a pest by communities in Nauru and parts of Kiribati[28,35] but are widely valued for food in Melanesia. Careful assessments of the costs and benefits of Nile tilapia aquaculture for food production are needed to reconcile the important agendas for food security and biodiversity in this region[5,33]. Tilapia have been introduced and cultured widely in Asia for > 70 years as an important source of food and a base for livelihoods, but no clearly negative effects on biodiversity have been reported[29,36,37].

Asian carp have also been introduced to the cooler waters of PNG, where they are grown quite commonly, particularly at higher elevations. These fish have not proved to be as popular as Nile tilapia, however, which are easier to breed and reach market size more quickly[7]. The species of Asian carp introduced to the region include: common carp *Cyprinus carpio*, Chinese carp (silver carp) *Hypophthalmichthys molitrix*, bighead carp *Aristichthys nobilis*, grass carp *Ctenopharyngodon idella*, Indian carps (rohu *Labeo rohita*, catla *Catla catla* and mrigal *Cirrhina mrigala*), silver barb *Barbonymus gonionotus* and some other species of cyprinids[28]. Potential effects on biodiversity also need to be considered in further development of carp aquaculture[38]. However, because many carp species are already well established in the wild in PNG (Chapter 10), the potential benefits of expanding carp farming in river catchments where they already occur may outweigh any adverse effects on freshwater biodiversity.

11.2.1.2 Milkfish

The milkfish *Chanos chanos* is a large tropical species farmed widely in Asia[9,39]. It is the basis of a substantial industry in many countries with total production in the Philippines, for example, of 350,000 tonnes in 2008[40]. This species is popular for aquaculture because it is herbivorous/planktivorous and, although the adults live in the sea, the juveniles can be grown simply in coastal enclosures flushed by the tide, and in brackish and freshwater ponds[39,42]. Milkfish can be spawned and reared in captivity[43,44], but much of the industry in Asia is based on the capture and culture of juveniles caught from shallow coastal habitats[45,46]. Given the high costs of maintaining the broodstock for milkfish, much of the further development of milkfish farming in PICTs is also likely to be based on the capture of wild juveniles. Farming practices in Asia also include careful pond management to promote growth of 'lab-lab', a turf of flora and fauna that milkfish graze on, reducing the need for supplementary feeding[39,49].

Milkfish are important traditionally for food in Nauru and Kiribati, and aquaculture of this species has been launched there and in several other PICTs. For example, between 5 and 15 tonnes of milkfish per year have been produced in Kiribati, and 30 to 80 tonnes per year in Guam since 2000[40]. Palau has investigated production of small quantities of cultured juveniles for bait for tuna longlining operations[41] and is now growing-out fry imported from the Philippines for both food and bait. These enterprises based on hatchery production or collection of wild juveniles have had mixed success. The market price and scale of production have often not been sufficient to cover costs without subsidy.

If reliable sources of wild juveniles can be identified, and feed based on local inputs can be formulated, there may be scope to produce hundreds of tonnes of milkfish per year in the region. There is continued interest in developing this potential, for example village-level capture and culture operations are under consideration in Fiji[50], and the grow-out of wild-caught juveniles for tuna bait is being evaluated at Penrhyn Atoll, Cook Islands.

11.2.2 Commodities for livelihoods

The high diversity of coastal fish and invertebrate species in the Western and Central Pacific Ocean (Chapter 9), and the large number of sheltered, pristine lagoon sites for aquaculture operations, provide several PICTs with opportunities to develop commodities for niche markets. Such coastal aquaculture activities can provide coastal communities with a source of income[10,12,51]. Commodities such as cultured pearls, shrimp, seaweed and marine ornamentals are already helping fulfil the aspirations for economic development and livelihoods based on aquaculture in a few PICTs. The range of commodities capable of supporting livelihoods, for which the region may have a comparative advantage, are listed in **Table 11.2** and described in more detail below.

11.2.2.1 Pearls

Pearls produced from pearl oysters (Pteriidae) are the region's most valuable aquaculture commodity[24], driven by international demand for round pearls and mother-of-pearl products. Pearl farming has proved to be viable in the region because (1) the oysters are available either from harvesting wild shells[52,53], collection of wild spat[54,55], or production of spat in hatcheries[53,56]; (2) grow-out methods for pearl oysters are simple – no feed inputs are needed[53]; (3) there are many protected and pristine lagoon environments for holding the oysters while the pearls are formed; (4) the technicians needed to operate on adult oysters to produce cultured pearls have been willing to visit even the remotest parts of the region[54]; and (5) the high-value products are non-perishable and have negligible shipping costs[57].

Almost all production is for 'black' pearls produced by the black-lipped pearl oyster *Pinctada margaritifera*[24]. Limited enterprises are underway for white pearls produced from the silver- or gold-lipped pearl oyster *Pinctada maxima* in PNG, and the winged pearl oyster *Pteria penguin* in Tonga, currently farmed for mabè (half pearls). There is also a market for the shells of cultured pearl oysters, and the handicrafts made from them[58].

Black-lipped pearl oysters, Fiji

Photo: Leanne Hunter

Although production of black pearls is currently dominated by French Polynesia (**Table 11.1**) where production of raw pearls has been between 10 and 13 tonnes per year over the past 10 years (**Figure 11.2a**), the technological advances in hatchery techniques and widespread knowledge of pearl farming could promote the culture of black pearls in many other PICTs. Viable black pearl farms have been established in Cook Islands, Fiji, Federated States of Micronesia (FSM) and Marshall Islands, and pilot projects have been launched in Kiribati and Solomon Islands[59,60]. In practice, however, there is a high risk of failure at many potential locations due to the nature of financial investments, uncertainty of long-term access rights where customary marine tenure exists, lack of infrastructure and likelihood of cyclones. In PNG and Solomon Islands, investors are more inclined to consider enterprises based on silver-lipped pearl oysters because the generally larger pearls they produce usually attain higher prices than black pearls.

In 2007, the value of pearl production from the region, including unreported sales, domestic sales, and exports of matched pearls, is estimated to have been USD 190 million. This represents about 25% of the total annual global value of marine pearl production[60]. The scale of this production, and competition from other regions, is forcing pearl farms to achieve economies of scale by increasing the number of cultured oysters to > 200,000. Producers are also expected to supply two market segments – the higher-value market for quality round pearls, and the lower end demand for baroque, keshi and 'circle' pearls, and half pearls, where there is strong competition from Chinese freshwater pearls. Because the demand for high-value round pearls is considered to be inflexible, it has been suggested that the region should reduce supply[57]. However, an alternative strategy to maintain or further increase revenue among the PICTs already producing pearls, and to allow more PICTs to engage in pearl farming, is to increase the percentage of top-quality pearls produced through better seeding and husbandry practices.

11.2.2.2 Shrimp

Shrimp (Penaeidae) are the basis for the second-largest aquaculture industry in the region, after black pearls. The industry in New Caledonia dominates production. It was launched in 1978, with the total harvest increasing to ~ 2000 tonnes per year by 1999, where it has remained for the past 10 years[24] (**Figure 11.2b**). Although significant regionally, New Caledonia is still a small producer of shrimp compared with countries in Asia[13]. Other PICTs currently involved in shrimp farming are Fiji, French Polynesia, Guam, Commonwealth of the Northern Mariana Islands (CNMI), PNG and Vanuatu. In New Caledonia, shrimp farming is the leading agro-food export (worth ~ USD 29 million per year) and provides valued employment opportunities in remote rural areas (~ 560 jobs). The availability of possible future sites suitable for this activity on the west and north coasts of New Caledonia would enable the original plans to produce around 4000–5000 tonnes per year to be fulfilled, if local socio-economic conditions and international market opportunities permit.

Although about 10 species of penaeid shrimp occur naturally in the region, including the black tiger shrimp *Penaeus monodon* cultured in Australia, the industry in New Caledonia is based on the blue shrimp *Litopenaeus stylirostris* from Central America. This species commands an excellent price when exported to niche markets, and was introduced because of its suitability to the cooler climate in New Caledonia[61–63]. In contrast, *P. monodon*, the species that has been farmed in PNG and Fiji, has a marked reduction in growth in New Caledonia during winter[64].

The main viral pathogens affecting penaeid shrimp farming around the world have not generally posed problems for PICTs; however, aquaculture of *L. stylirostris* in New Caledonia is affected by seasonal outbreaks of vibrio bacteria[65,66]. This pathogen, which appears to be triggered by unstable pond temperatures during the short spring and autumn seasons, can cause heavy losses of shrimp, and limits the New Caledonia industry to a single crop cycle per year[67].

The development of penaeid shrimp farming in other PICTs has been slow due to the lack of local technical capacity in aquaculture, capital, infrastructure, and research and development support from governments.

11.2.2.3 Seaweed

Farming seaweed is conceptually appealing to coastal communities in several PICTs because it is a low-technology operation suitable for both men and women with a quick return on labour. The seaweed species in demand, *Kappaphycus alvarezii*, can be harvested from cuttings within 6 weeks[68]. Until recently, seaweed farming was a mainstay of the economy in Kiribati; production began in the mid-1980s and peaked at 1400 tonnes dry weight in 1999, but has decreased markedly in recent years[24] (**Figure 11.2c**). The culture of *Kappaphycus* also varied between 0 and 300 tonnes per year in Fiji over a similar period. More recently, the seaweed has also been grown in Solomon Islands, with harvests reaching 400 tonnes in 2009[69], and 800 tonnes in 2010. Based on estimates of the area of lagoons suitable for seaweed farming in Solomon Islands and Fiji, production levels at least 2000 tonnes per year could be possible for each country.


Photo: Georges Steinmetz

Seaweed farm, Tabiteuea Atoll, Kiribati

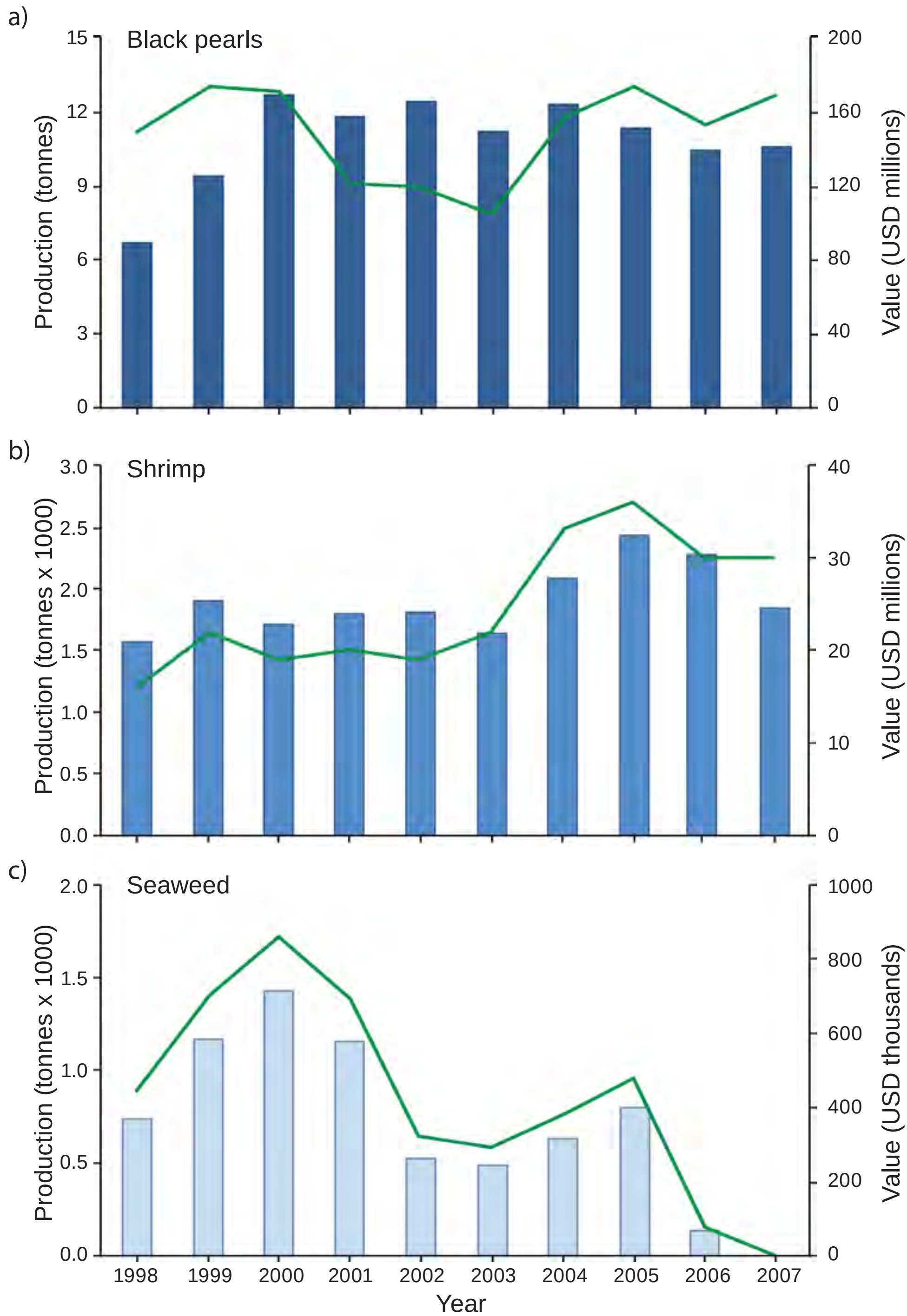


Figure 11.2 Production of (a) all black pearl products in French Polynesia, (b) shrimp in New Caledonia, and (c) seaweed in Kiribati between 1998 and 2008; the green line represents the value of production (source: Ponia 2010)[24].

There are constraints to farming *Kappaphycus*, however. Dried seaweed is a low-value bulk commodity so seaweed aquaculture has difficulty competing with alternative livelihood options (e.g. fishing for sea cucumbers) except in very remote areas where there are few alternative opportunities to earn income. However, transport costs from such areas to shipment points and centralised export operations can be prohibitive. There can also be seasonal or site-specific losses due to grazing by herbivorous reef fish (such as siganids); epiphytic filamentous algae, which colonise the seaweed thalli and stunt growth; or rough sea conditions. Such problems need to be addressed through appropriate site selection. In a few communities, the availability of space and building materials to construct seaweed drying platforms is a limitation. In these places, cost-effective and sustainable alternatives to cutting mangroves for timber to build platforms need to be found[69].

Potential for culture of other species of seaweed is based mainly on *Cladosiphon* sp., which has been commercially harvested in Tonga for the Japanese domestic food market[21].

11.2.2.4 Marine ornamentals

Although a variety of live marine ornamental fish and invertebrates are exported from PICTs for the aquarium market (Chapter 9), aquaculture currently contributes substantively to only two of these products: corals and giant clams. However, culture of 'live rock' (decorative, small coral boulders covered in encrusting organisms and crustose coralline algae which act as biological filters in aquaria) is now moving to a pilot commercial scale in Fiji and Tonga. There is no hatchery-based production of marine ornamental fish in PICTs, although juvenile fish, cleaner shrimp and spiny lobsters caught from the wild and reared for several weeks in 'postlarval capture and culture' operations[46–48] are under development in French Polynesia and Solomon Islands.

Coral farming is based on the collection and grow-out of fragments from wild colonies[70]. The technology is simple, low cost, and suitable for small-scale operations and for self-employment of rural women and youth. In 2007, more than 77,000 pieces of cultured coral were produced in Fiji, FSM, Marshall Islands, Solomon Islands and Vanuatu combined[71]. In addition to supplying the aquarium market, cultured corals can be used for coral reef restoration, enhancement of snorkeling trails at tourism sites, and sale to the curio trade, where higher prices are paid for cultured corals than for wild specimens.

Six of the eight species of giant clams in the Pacific (*Tridacna crocea*, *T. derasa*, *T. gigas*, *T. maxima*, *T. squamosa*, and *Hippopus hippopus*) (**Figure 11.3**) have been produced in hatcheries, grown-out in cages in 'village farms' or in land-based facilities, and sold to the aquarium trade by PICTs[72–75]. Cultured giant clams have also been placed in the wild in limited restocking operations[76]. The hatchery and grow-out methods are straightforward[72,77,78] and had been applied in 11 PICTs by the late 1990s[79], and in 17 PICTs by 2007[80]. The combined exports of cultured giant clams from Cook Islands, FSM, Kiribati, Marshall Islands, Palau, Solomon Islands, Vanuatu and Tonga totalled 75,000 pieces in 2007[81].

Figure 11.3 The six species of giant clams that have been cultured in the tropical Pacific: *Tridacna maxima* (top left), *T. gigas* (bottom left), *Hippopus hippopus* (top centre), *T. derasa* (bottom centre), *T. squamosa* (top right) and *T. crocea* (bottom right) (photo: Mike McCoy).

11.2.2.5 Freshwater prawns

Techniques for farming freshwater prawns in the genus *Macrobrachium* have been developed in many countries[82]. These prawns are not a global commodity on the same scale as penaeid shrimp, but their importance is steadily growing and in 2008 their global value was 66% of that of tilapia[83]. Worldwide, most of the production is based on *Macrobrachium rosenbergii*[82] but this species does not occur naturally in PICTs except in PNG. It has been introduced to several parts of the region for aquaculture trials (e.g. Fiji, French Polynesia and Solomon Islands), although there are no reports of it becoming established in the wild. However, captive stocks of *M. rosenbergii* in the region are currently limited to one population maintained by hatchery production in Fiji. This stock forms the basis of an emerging aquaculture industry, with production of ~ 25 tonnes per year, mainly from one medium-sized farm (8 ha). Other PICTs are interested in engaging or re-engaging in farming *M. rosenbergii* and, considering the strengthening demand for freshwater prawns, there is potential for producing several hundred tonnes per year across the region.

The local market for freshwater prawns is supplied mainly by the capture of the indigenous *Macrobrachium lar* (Chapter 10). The prospects for hatchery-based aquaculture of this species do not look good, however, because it has a long and complicated larval stage[84]. Farming of *M. lar* will need to be based on capture and grow-out of juveniles caught from the wild. Preliminary trials suggest that this may be possible on a small (household-level) scale[85].

11.2.2.6 Marine fish

High-value tropical marine food fish of potential interest for aquaculture in PICTs are mainly groupers (Serranidae), which form the basis for the international live reef fish trade. Due to a rapid increase in demand from China, and limited stocks in the wild[86,87], culture techniques have been developed in Asia and Australia to supply these highly-prized fish[88]. However, these methods require considerable investment in sophisticated hatcheries and the infrastructure for growing fish to market size. They also depend on large quantities of fresh fish as feed or expensive imported high-protein, formulated diets. The high costs of operating such facilities in PICTs, and the competitive advantage of marine fish farming operations in Asia (with lower labour costs and better proximity to markets), argue against development of enterprises in PICTs to supply the live reef fish trade[89].

The only hatchery-based marine fish farming operations in the region are modest enterprises for barramundi *Lates calcarifer* in PNG, CNMI (Saipan) and Vanuatu, batfish *Platax orbicularis* in French Polynesia, rabbitfish *Siganus lineatus* in New Caledonia, and milkfish *C. chanos*, rabbitfish *Siganus* spp. and the coral trout *Plectropomus areolatus* in Palau.

The often high but variable availability of juvenile rabbitfish (Siganidae)[90] in many PICTs provides the potential for grow-out operations for this species and some research on the best methods and feeds for such aquaculture has been done[91,92]. Although rabbitfish are a popular food fish in the western Pacific, it remains to be seen whether the reliability of capture and culture operations, and local market demand, are good enough to make aquaculture viable.

11.2.2.7 Sea cucumbers

There has been considerable investment within the region in the development of methods for producing the sandfish *Holothuria scabra* in hatcheries, and releasing the juveniles in the wild. The work was pioneered by the WorldFish Center in Solomon Islands[93–98] and in New Caledonia[99–103]. The focus has been on sandfish because it has proved to be the easiest of the tropical sea cucumbers to rear in captivity, and commands one of the highest prices per kilogram when processed into bêche-de-mer[104,105]. Another of the highly valuable sea cucumbers, the white teatfish *Holothuria fuscogilva*, has also been reared in Kiribati, and released in limited quantities in nearby coastal habitats[106,107]. However, the techniques for propagation and release of *H. scabra* are far more advanced.

The ability to produce juvenile sandfish in hatcheries creates the opportunity to grow-out this species in earthen ponds in much the same way as sea cucumber are cultured in China[104]. Whether this can be done competitively in New Caledonia, with its relatively high labour costs and slow rates of growth, remains to be seen[102]. More emphasis is being placed on the use of cultured juveniles for restocking overfished populations, and for sea ranching initiatives[108]. Building on recent work in New Caledonia[103], sea ranching trials for sandfish are now underway in Fiji[109].

PICTs in Melanesia meet many of the pre-requisites for restocking and sea ranching sandfish including (1) extensive areas of seagrass (Chapter 6), which provide essential habitat for this species[110]; (2) severely overfished populations (Chapter 9), which provide few options for replenishment apart from restocking[105,111,112], and vacant habitat for sea ranching; and (3) local tenure arrangements that enable coastal communities to benefit from releases of hatchery-reared juveniles. Whether survival rates of cultured juveniles in the wild will justify the costs of producing and releasing them still needs to be determined.

11.2.2.8 Trochus

The topshell *Trochus niloticus*, also commonly known as trochus, provides an important source of income for coastal fishing communities in many PICTs[113], but stocks have now been fished to chronically low levels in many parts of the region (Chapter 9). Overfished stocks can be restored and new fisheries can be established simply by translocating adults and imposing a moratorium on fishing until the populations are robust enough to sustain harvests[76]. However, methods have also been developed to produce trochus in hatcheries for release in the wild[114,115]. Where hatchery-based release programmes are deemed to be necessary, combining the culture of giant clams and trochus has been proposed as a way of reducing the cost of rearing trochus to a size where they have reasonable chances of survival in the wild[116]. There is also a limited market for trochus in the ornamental trade. In 2007, Marshall Islands produced 5000 pieces of trochus for this market.

11.3 Vulnerability of aquaculture to the effects of climate change

Aquaculture is vulnerable to climate change in more ways than fisheries. The vulnerability of fisheries is due mainly to the direct and indirect effects of climate change on the abundance and distribution of species that provide the harvests (Chapter 1). Although more severe weather may mean that catches must be postponed until it is safe to fish again, the effects of climate on fishing operations are usually likely to be less important than the response of the target species, and the habitats they depend on, to the changing environment (Chapters 5–10).

For aquaculture, however, both the organisms that are produced in hatcheries or collected from the wild as 'seed' and grown to market size, and the farming operations and infrastructure themselves, are subject to the direct and indirect effects of climate change[117]. Changes to temperature and rainfall, and their effects on salinity and oxygen, can be expected to affect the reproduction, growth and survival of the organisms selected for aquaculture. Similarly, for those species collected as juveniles from the wild, changes to the habitats on which the adults depend may affect the economic viability of relying on the collection of wild juveniles for grow-out.

The fact that much of the infrastructure for aquaculture (e.g. ponds) cannot usually be moved to prevent damage from severe weather conditions means that aquaculture is more exposed to the direct effects of climate change than fishing fleets, which can be relocated to secure harbours. Other examples of the indirect effects of climate on the viability of aquaculture operations include (1) the reduced availability and higher cost of feed ingredients due to the effects of the El Niño-Southern Oscillation (ENSO) on the supplies of fishmeal and the impacts of drought on crops, and (2) the failure of energy supplies due to natural disasters.

Here we apply the vulnerability framework described in Chapter 1 to these two main components of aquaculture – the species that underpin production, and the farming operations themselves. We consider the direct and indirect potential impacts of climate change on both components of aquaculture for each of the main commodities produced in the region for food security and livelihoods.

11.3.1 Vulnerability of commodities for food security

11.3.1.1 Tilapia and carp

Exposure and sensitivity

- **Temperature:** Tilapia and carp are typically cultured in earthen ponds where prevailing rainfall patterns provide sufficient surface or ground water to keep the ponds filled. Water temperatures in these farming systems in the tropical Pacific are projected to increase in line with those for surface air temperature, i.e. by 0.5–1.0°C under the B1 and A2 emissions scenarios in 2035, by 1.0–1.5°C for B1 in 2100 and by 2.5–3.0°C under A2 in 2100, relative to 1980–1999 (Chapter 2).

  Tilapia and carp farming are expected to be sensitive to the projected increase in temperature because the distribution of these operations in Melanesia is currently limited by the effects of cooler conditions on reproduction and growth of these species at higher altitudes. In particular, feeding of tilapia is reduced sharply at temperatures < 20°C and spawning is not possible below 22°C[118]. Mortality of tilapia occurs if there is prolonged exposure to temperatures < 12°C[119–121], with fingerlings being more sensitive than adults[122]. Among tilapia, *Oreochromis mossambicus* is the most cold-sensitive species[123]. At the other end of the scale, tilapia can tolerate temperatures up to 42°C[118], although exposure to high temperatures results in more deformities in early larval stages, and sex ratios skewed towards males[118]. Even within the optimal temperature range for reproduction, development and growth of tilapia (25–30°C)[118–120,124,125], maintaining water temperatures closer to the upper end of this range can make a big difference to the productivity of tilapia aquaculture[118].

The optimum temperature range for growth of common carp is similar to tilapia, at 23–30°C. Carp are much more cold-tolerant than tilapia, however. For example, bighead and silver carp can tolerate temperature extremes typical of cold temperate to tropical regions, and have similar optima for growth to common carp[126].

The ecosystems in tilapia and carp ponds are also sensitive to changes in water temperature. Higher temperatures can cause stratification, leading to algal blooms and reduced levels of dissolved oxygen (**Figure 11.4**). Tilapia can tolerate dissolved oxygen concentrations as low as 0.1–0.5 mg/l, but only for limited periods[127]. Fish can avoid potentially lethal areas in stratified ponds but this reduces the volume of available habitat and increases the stress on fish congregated in non-lethal areas. Heat stress can also occur due to elevated temperatures and is exacerbated in shallow-water ponds (< 50 cm deep) compared with deeper-water ponds (100–200 cm deep), where fish can 'escape' by staying lower in the water column during summer and moving towards the surface in winter[118].

Overall, tilapia and carp are considered to be relatively hardy fish for aquaculture but repeated or prolonged exposure to extreme temperatures and low dissolved oxygen levels, especially at high stocking densities, can be expected to increase stress and the susceptibility of the fish to disease (Section 11.3.4).

- **Rainfall:** In tropical Melanesia, where most pond farming for tilapia and carp is expected to occur, rainfall is projected to increase by 5–15% under the B1 emissions scenario in 2035, by 5–20% under A2 in 2035, and by 10–20% under B1 and A2 in 2100, relative to 1980–1999 (Chapter 2). Also, wet and dry periods are expected to become more extreme (Chapter 2).

  Growing tilapia in small ponds at a low stocking density (2 fish per m^2) without exchanging the water, which is a common form of subsistence aquaculture in inland PNG[7], is expected to be favoured by the projected increases in rainfall because this farming system depends on rainfall exceeding pond evaporation[128].

In general, the projected increases in rainfall are likely to expand the distribution of the areas where tilapia farming based on low or zero water exchange occurs.

- **Sea-level rise:** The rates of sea-level rise projected in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change are acknowledged to be conservative – more recent estimates are that sea level will rise by 20–30 cm under the B1 and A2 emissions scenarios in 2035, by 70–110 cm under B1 in 2100 and by 90–140 cm under A2 in 2100 (Chapter 3). The penetration of saline water further inland is expected to render some of the existing ponds near the coast unsuitable for Nile tilapia and carp because reproduction and growth of these species is greatest at salinities < 5 practical salinity units (PSU)[129,130]. Salination of ponds in areas subject to sea-level rise may be mediated by the projected increases in rainfall.
- **Cyclones:** Although cyclones are not projected to become more frequent, they may become more intense (Chapter 2). Floods caused by cyclones and more extreme rainfall events are expected to be a threat to tilapia ponds constructed in low-lying areas or close to rivers. Flooding could result in damage to ponds and other farm infrastructure, and the escape of fish through 'over-topping' of pond dykes by rising waters.

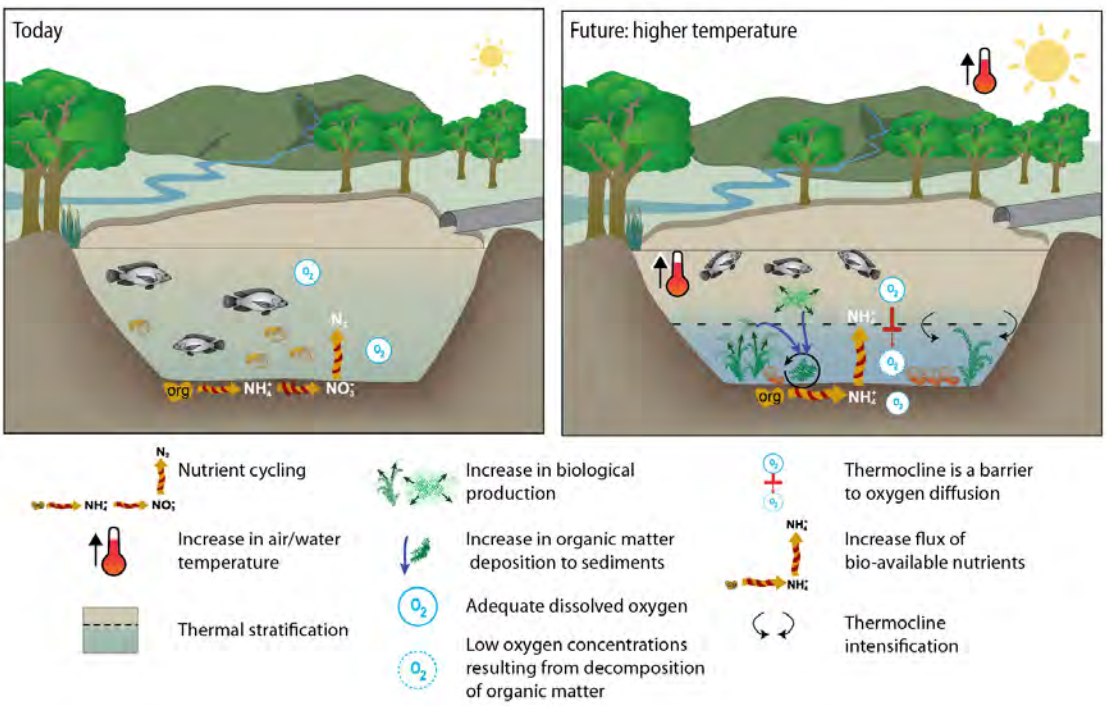


Figure 11.4 Effects of projected higher water temperatures on stratification in freshwater aquaculture ponds and the consequences for levels of dissolved oxygen.

Potential impact and adaptive capacity

The direct effects of projected increases in temperature are not expected to affect the suitability of lowland habitats in the region for tilapia or carp farming. In fact, production is likely to increase in lowland areas above the influence of rising sea levels and floods due to enhanced growth rates at higher temperatures and greater availability of fresh water for pond aquaculture. Increased deformities may affect production if prolonged periods of high temperatures occur in the low-lying equatorial areas. However, any effects on sex ratio may not affect production adversely because tilapia farmers often strive to produce male fingerlings for grow-out[131].

The warmer and wetter conditions are also expected to enable tilapia and carp to be grown at higher altitudes and at more locations at these altitudes, increasing the potential area where tilapia and carp can be produced. Expansion of suitable areas for farming tilapia would benefit inland communities in PNG, which have limited access to animal protein (Chapters 1 and 10)[4].

On the negative side, higher temperatures are likely to increase stratification in ponds with low water exchange, reducing production and increasing the risk of disease (Section 11.3.4) (**Figure 11.4**). The occurrence of stratification is, however, expected to be reduced by the benefits of the projected increases in rainfall on pond mixing and turnover. In other places, flooding from more intense cyclones and more frequent extreme rainfall events could damage ponds and cause loss of fish.

Adaptations to reduce any eventual adverse effects of warmer pond temperatures have focused on locating and constructing ponds to increase the mixing of water, either by mechanical means or by increased turnover. Increased turnover should be balanced against the need to maintain plankton blooms to provide natural food, and minimise the cost of supplementary feeding. Where possible, ponds should be placed at sites not exposed to floods, that receive an abundant supply of water through gravity-flow. This will allow lengthwise laminar flow of inlet water at the surface, and drainage through outlets placed at the bottom of the pond. In locations without access to strong flows, or where water has to be pumped, paddle-wheel aerators can be used to reduce stratification. However, the cost involved in such adaptations is likely to eliminate small-holders from farming tilapia where stratification is a problem.

Because intensive tilapia farming enterprises growing fish for urban markets depend heavily on formulated diets with ~ 20% protein, changes in the availability of fishmeal may indirectly affect tilapia production. Formulated feeds comprise 30% of costs for tilapia farming in Fiji, and increases in the price of fishmeal may affect the viability of these enterprises. The risks are due to the broader effects of climate change on (1) the abundance of the small pelagic fish in South America used to produce the fishmeal; and (2) the supply of tuna to processing plants in the region that make fishmeal as a by-product.

Tilapia and carp farming have a high capacity to adapt to a changing climate – both species can be produced simply and reared cost-effectively under a broad range of warm-water temperatures, and stocked at a wide range of densities and water exchange rates. Enterprises based on intensive culture systems have a lower adaptive capacity than small ponds used for subsistence, where stocking densities can simply be altered to suit the prevailing conditions and availability of fish feeds. Ultimately, the capacity for tilapia and carp farmers to take up any opportunities created by a changing climate will depend on the measures that PICTs implement to promote small pond aquaculture, within the context of reconciling plans to promote food security and maintain biodiversity[33].

Vulnerability

The farming of tilapia and carp in the tropical Pacific has little or no vulnerability to climate change. Indeed, if PICTs decide that tilapia and carp farming is a responsible way to increase the availability of fish for food security, climate change is likely to have a low, positive effect on production by 2035 under the B1 and A2 emissions scenarios. In particular, the higher temperatures and increased availability of fresh water are expected to favour pond aquaculture in tropical Melanesia. Low to medium positive effects on production are likely to occur under B1 by 2100, increasing to medium positive effects under A2 by 2100.

11.3.1.2 Milkfish

Exposure and sensitivity

- **Temperature:** The life cycle of the milkfish, and all aspects of its farming in brackish or fresh water, are also expected to be exposed to the increases in sea surface temperature (SST) described in Section 11.3.2.1, and Chapters 2 and 3.

  Warmer SST is expected to lead to an expansion of the range of adult milkfish and the seasonal availability of fry. Milkfish occur where SST exceeds 20°C, and fry are common in coastal habitats once SST reaches 27°C[39,132]. Also, the length of the season for collecting fry is positively correlated with SST[133]. Warmer temperatures in ponds are projected to increase growth rates, and improve the efficiency of food conversion ratios[134].

- **Rainfall:** The projected increases in rainfall (Section 11.3.2.1, Chapter 2), which are expected to result in increases in precipitation of 5–20% in the tropics under the B1 and A2 emissions scenarios by 2100, are likely to increase the number of locations where milkfish can be farmed in freshwater ponds. However, reductions in salinity due to increased rainfall may change the distributions of postlarvae recruiting to coastal habitats.

- **Ocean acidification:** Postlarval milkfish are projected to be exposed to progressive acidification of the ocean (Chapter 3). The effects of acidification on the recruitment success of milkfish larvae have not been studied. However, experiments involving the postlarvae of some coral reef fish indicate that survival is likely to be reduced at lower pH due to the adverse effects of ocean acidification on behaviour (Chapter 9).

- **Sea-level rise:** Milkfish should not be sensitive to the projected changes in sea level outlined in Section 11.3.2.1 and Chapter 3 because they can be grown in a wide range of salinities. However, sea-level rise may require ponds to be moved further inland to prevent damage from wave surge and loss of fish from inundation.
- **Cyclones:** Milkfish farming is expected to be more exposed to the physical damage caused by the projected intensification of cyclones (Chapter 2) than tilapia and carp aquaculture because most milkfish ponds and cages are located close to the coast.
- **Habitat alteration:** Milkfish farming enterprises in PICTs may be exposed to changes in the availability of milkfish fry, due to the effects of climate change on coastal habitats. Increased variation in the supply of juveniles is likely to stem from changes to the location and suitability of inshore habitats for collection of fry, caused by changes in the areas of mangroves, seagrasses and intertidal flats[135–137] (Chapter 6). Alterations to these habitats are expected to be driven by increasing temperatures, sea-level rise, and variation in coastal currents and salinity regimes (Chapters 3 and 6).

Milkfish ponds, Vitawa Village, Fiji

Photo: Timothy Pickering

Potential impact and adaptive capacity

The direct effects of the projected increases in water temperature are likely to be beneficial to milkfish farming in the tropical Pacific. In particular, they are expected to (1) lengthen the season in which wild fry are available for stocking ponds; (2) extend the geographical range of milkfish spawning to higher latitudes; and

(3) reduce the time to harvest. Increased rainfall is also likely to provide more options for growing milkfish in freshwater ponds. The potential impact of any changes in the location and availability of wild juveniles for stocking ponds is difficult to estimate because the industry has yet to develop. However, sufficient quantities of juveniles are expected to be available in some PICTs – it just remains to be seen where these locations will be. Milkfish farming could be affected indirectly by increases in the availability and cost of fishmeal. The relatively low value of milkfish would make it difficult for enterprises to operate economically in the face of increased prices for feed, which is often the major aspect of production costs[39].

In the event that milkfish farming based on the collection of wild fry is affected by increased variability in the supply of juveniles, the industry may be able to adapt by producing juveniles in hatcheries. This is an expensive option, however, and only likely to be viable if the industry grows to a large size and has comparative advantages that enable other production costs to be reduced. The herbivorous/planktivorous diet of milkfish allows farmers to adapt to shortages of fishmeal in formulated diets by applying lab-lab pond management techniques, and replacing much of the fishmeal in formulated diets with plant protein[138].

Vulnerability

Milkfish farming in the tropical Pacific appears to have little or no vulnerability to climate change. Indeed, plans to develop milkfish farming in the region are expected to benefit from a low, positive effect of climate change on production under the B1 and A2 emissions scenarios by 2035. The potential benefits stem from the expected extension of the geographical area suitable for collection of fry and pond culture due to increasing water temperatures and rainfall, and increased rates of production within the present-day distribution of the species in the tropical Pacific. The level of potential benefits in 2100 is uncertain due to the possible increased adverse effects from continuing acidification of the ocean and habitat alteration on the supply of juveniles. Until these effects are better understood, any benefits for milkfish farming in 2100 should be considered to remain low.

11.3.2 Vulnerability of commodities for livelihoods

11.3.2.1 Pearls

Exposure and sensitivity

- **Temperature:** The significant pearl farming enterprises in French Polynesia, Cook Islands and Fiji, those underway in FSM, Marshall Islands, PNG and Tonga, and those planned for Kiribati and Solomon Islands, are projected to be exposed to increases in SST within the range of 0.5–1.0°C by 2035 under the B1 and A2 scenarios, and 1.0–1.5°C and 2.5–3.0°C under B1 and A2 in 2100, respectively (Chapters 2 and 3).

These important regional aquaculture activities are expected to be sensitive to increases in SST because temperatures > 28–32°C increase the susceptibility of pearl oysters in general to pathogens and parasites[139,140]. For example, harmful algal blooms can form when high temperatures increase stratification of coastal waters (Chapter 3) and/or when runoff from land during heavy rainfall increases nutrient loads (Chapter 7). 'Red tides' (*Heterocapsa* sp.) caused by such conditions have led to mass mortalities of Akoya pearl oysters in Japan, and large economic losses[141]. Water temperatures > 29°C have also been linked to mass mortalities (70%) of Akoya pearl oysters[142].

The thickness and deposition rate of nacre laid down by pearl oysters, and therefore pearl quality[143,144], is also likely to be sensitive to increases in SST. It is generally accepted that higher-quality nacre with superior lustre is deposited when water temperatures are cooler[145]. The rate of nacre secretion increases at warmer temperatures[146] and, although this allows production of larger pearls over a fixed period or earlier harvest of pearls of minimum market size, it could result in reduced pearl quality.

- **Rainfall:** The pearl industry in the tropical Pacific would have a varied exposure to projected changes in rainfall. Rainfall is generally expected to increase in equatorial areas, and decrease in the subtropics, by 5–20% in 2035 and 10–20% in 2100 (Chapter 2).

The more extreme rainfall events likely to occur in the future would cause abrupt decreases in salinity of coastal waters, increased sediment loading and rapid changes in the productivity of coastal waters. These changes can lead to mass mortality of oysters[147–149], for example, when the excessive filtration of suspended solids by oysters in turbid water exceeds their energy budget[149–151].

The sensitivity of pearl farming to higher rainfall is expected to depend on the location of operations. Farms in French Polynesia and Cook Islands, where most production occurs, will not be exposed to reduced salinities because rainfall is projected to decrease in subtropical areas. Even if extreme rainfall events do occur occasionally, there is little scope for runoff from atolls where farms are situated. Those pearl farms in FSM, Kiribati and Marshall Islands that have the benefit of being in atolls are not expected to be sensitive to the projected increase in rainfall. Farms established in lagoons in FSM, PNG, Solomon Islands and Fiji under the influence of runoff from high islands would be at increased risk of losing oysters due to reduced salinity and increased nutrient loads. Throughout Melanesia, increased rainfall could interact with warming SST to increase stratification and the incidence of harmful algal blooms (Chapters 2 and 3).

- **Ocean acidification:** The pH of the tropical Pacific Ocean is projected to decrease by 0.1 units by 2035 under the B1 and A2 emissions scenarios, and by 0.2–0.3 units by 2100, relative to the 1980–1999 average (Chapter 3). Little is known about the sensitivity of pearl oysters to this exposure, but the information available for other marine invertebrates, and for other species of oysters that construct shells and skeletons from calcium carbonate (Chapters 3 and 5), indicates that pearl oysters are likely to be badly affected by long-term declines in pH. Like many other marine invertebrates, acidification of the ocean is expected to limit the development of larvae and increase the percentage of individuals with abnormal shells[152,153,157–159]. These deficiencies would be expected to result in greater rates of predation and mortality, leading to reduced availability of oyster spat on collectors.

The fitness of surviving adults is also expected to be affected. Calcification rates of both the Pacific oyster *Crassostrea gigas* and the Atlantic oyster *C. virginica* are projected to decrease with declining aragonite saturation[160,161]. Decreases in calcification can reduce growth rates and lead to thinner or more fragile shells, causing oysters to be more susceptible to boring pathogens and mechanical disturbance, which ultimately results in increased mortality[162]. Shells of the pearl oyster *Pinctada fucata* exposed to acidified sea water (pH 7.8 to 7.6) for 28 days showed a 26% reduction in strength compared to controls, presumably as a result of dissolution[163]. Furthermore, adult *P. fucata* secreted fewer and thinner byssal threads under acidified conditions, indicating impaired physiological function, greater susceptibility to mechanical disturbance and loss from culture equipment[163].

There are also concerns that ocean acidification will reduce the quality of pearls. Although the shell of adult pearl oysters is dominated by calcite, the less soluble of the two forms of calcium carbonate used by marine invertebrates to construct their skeletons and shells (Chapter 3), the nacre of pearl oysters is composed mainly of the more soluble aragonite. Exposure of live *P. fucata* to acidified conditions (pH 7.8 to 7.6) resulted in malformation and/or dissolution of nacre at its growing edge[163]. Ocean acidification could affect the quality of half pearls (mabè) grown on the inner surface of pearl oyster shells, but its potential impact on round pearl quality is less clear. Round pearls develop within an oyster's tissues and are not in direct contact with ambient conditions. However, impaired physiological function under acidified conditions[163] could influence the rate at which nacre is deposited onto pearls as they form, and nacre quality.

- **Sea-level rise:** The projected rises in sea level (Section 11.3.2.2, Chapter 3) are likely to result in more frequent over-topping of atoll reefs by ocean swells, leading to increased current velocity and reduced residence time of sea water in enclosed lagoons. Pearl farming operations are expected to be sensitive to these changes because currents are essential for delivery of food (suspended organic particles) to the sessile oysters[164]. Greater supplies of food result in faster rates of nacre secretion, although the nacre deposited under such conditions is usually of lower quality[165]. Larvae may be washed out of the lagoons faster, thereby reducing pearl oyster recruitment rates.

- **Cyclones:** Pearl farming is expected to be highly susceptible to the projected increases in the intensity of cyclones (Chapter 2). In addition to the increased mechanical disturbance of the water column causing greater stress and mortality of oysters, more severe storms would be expected to inflict greater damage to farm infrastructure. The heavy seas and high winds caused by Cyclone Tomas in Fiji in March 2010 provide a recent example of the adverse effects of cyclones on pearl farming. Cyclone Tomas destroyed pearl seeding platforms, inundated a hatchery and swept away seawater intake pipes. Cyclones may also cause oligotrophic conditions leading to mass mortalities of pearl oysters due to the favourable conditions created for pathogens[166].

Potential impact and adaptive capacity

The projected increases in SST by 2035 are likely to have little effect on the growth and survival of *P. margaritifera*, which produces black pearls in Polynesia. However, the higher SSTs projected for 2100, particularly under the A2 scenario, may stress *P. margaritifera* in the warmer months of the year. The silver-lipped pearl oyster *P. maxima* farmed in PNG is also likely to reach upper thermal limits for optimal growth during warmer months by 2100.

Ocean acidification is expected to progressively reduce the rates of spat collection due to increased susceptibility of spat with weaker shells to predation. Growth of oysters to adult size in atolls may not be affected if the benefits of faster growth stemming from stronger currents due to sea-level rise cancel out the effects of ocean acidification on shell growth. In lagoons around high islands, increased nutrient loads would be expected to drive the locations for collection of spat further offshore[54].

Perhaps the greatest potential impact on pearl farming in the region, however, will be the combined effects of higher water temperatures, increased current regimes and ocean acidification on pearl quality. The profitability of pearl farming operations is closely linked to the percentage of high-quality pearls produced[167] (**Figure 11.5**), and any significant decrease in pearl quality will have consequences for the economic viability of enterprises.

The pearl industry is in a reasonable position to adapt to some of the projected effects of climate change. Any effects of higher SSTs, ocean acidification and high nutrient loads on the collection of spat can probably be overcome by increasing the proportion of spat produced in hatcheries under controlled temperature and pH conditions, albeit at increased cost. It may also be possible to counter the effects of rising SST on pearl quality to some extent by placing the oysters at a greater depth, and harvesting the pearls during the cooler months of the year.

Combating the likely effects of ocean acidification on pearl quality will be difficult because pearl oysters cannot be maintained economically under controlled conditions for the time it takes to produce pearls – the oysters need to be held in sheltered marine areas. However, there may be scope for identifying areas that remain buffered against lower aragonite saturation states. Such places can be found near well-flushed, carbonate-rich coral reefs, and in close proximity to areas with a good cover of seagrass and macrophytes[168] (Chapter 6).

The design of the entire infrastructure of pearl farms needs to be assessed to increase durability under more intense cyclones. Placing pearl oysters in deeper water to reduce the adverse effects of higher SST on nacre quality should also reduce damage by storms.

Vulnerability

The production of pearls is expected to have a low vulnerability to the effects of global warming and ocean acidification under the B1 and A2 emissions scenarios in 2035. However, vulnerability is expected to increase to moderate towards 2100, particularly in the equatorial western Pacific. This assessment may well need to be revised 'downwards', however, once the results of research on the effects of reduced aragonite saturation on the larvae and adults of pearl oysters, and on pearl quality, are examined in detail.

a) b)

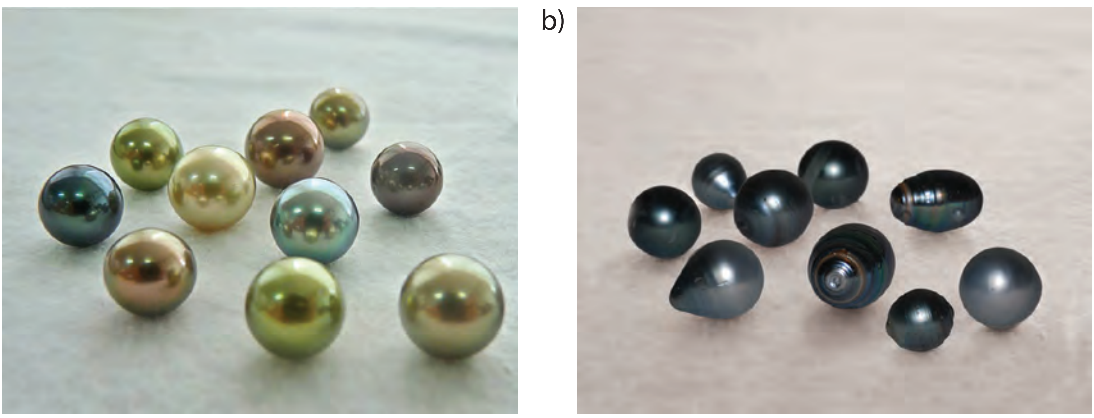


Figure 11.5 (a) High-quality pearls from black-lipped pearl oysters (photo: Leanne Hunter); and (b) low-quality pearls with poor lustre and surface defects (photo: Emily Naidike).

11.3.2.2 Shrimp

Exposure and sensitivity

- **Temperature:** The species of shrimp used in the region for aquaculture, *Litopenaeus stylirostris* in New Caledonia and Vanuatu, *Penaeus monodon* in Fiji and PNG, and *L. vannamei* in CNMI and Guam, are expected to respond to the changes in surface air temperatures projected to occur under the B1 and A2 emissions scenarios in 2035 and 2100 (Section 11.3.2.1, Chapter 2). The first two species are presently grown at the lower limits of their temperature ranges. In CNMI and Guam, *L. vannamei* is reared in intensive, closed, recirculating systems where temperature is easier to control.

The ideal temperatures for growth of *L. stylirostris* are between 24°C and 30°C[61]. Below 24°C, growth rates fall rapidly (up to 75% decrease at 20°C), and food consumption is reduced at temperatures > 30°C. Despite slower growth at lower temperatures, *L. stylirostris* was selected as the basis for the shrimp industry in New Caledonia because it had potential for year-round farming. However, fluctuations in pond temperatures during the relatively short autumn and spring transitions between the longer, more stable summers and winters, have caused chronic mortalities due to two vibriosis diseases, known as 'Syndrome 93' and 'Summer Syndrome'[169,170] (**Figure 11.6a**). The syndromes are linked to the stresses caused to shrimp by pond temperature variations of several degrees in only a matter of days.

The normal expectation for survival of *L. stylirostris* to harvest size in production cycles initiated in summer in New Caledonia is 60% if the effects of autumn and spring temperature transitions are weak. If the transitions are severe, however, vibriosis-induced mortality reduces survival to 35–40%[65]. Warming would be expected to lead to an improvement in survival in ponds seeded in the autumn (April–May) and winter (June–August). On the other hand, the success of the summer shrimp farming cycle for *L. stylirostris* depends on moderate summer temperatures because survival is correlated to the temperature during the first month of growth[62]. Thus, the summer production cycle may be adversely affected by the higher projected surface air temperatures. Male broodstock of *L. stylirostris* are also likely to be sensitive to increased temperatures – adult male shrimp held in earthen ponds already have problems producing viable sperm during the hottest months of the year (January–March)[171–173].

Penaeus monodon is more sensitive to cool water temperatures than *L. stylirostris*; growth of *P. monodon* slows once temperatures fall much below 28°C[174]. Variations in pond temperature also have pronounced effects on production of *P. monodon*, with maximal growth rates occurring during sustained warm periods[175]. In Fiji, poor growth and increased mortality of *P. monodon* have been associated with winter temperatures of 22–25°C.

- **Rainfall:** New Caledonia is expected to be exposed to reductions in rainfall of up to 20% by 2100 under the A2 scenario, with the drying occurring predominantly during winter (Chapter 2). Fiji, PNG and Vanuatu on the other hand, are projected to receive up to 20% more rain by 2100. Throughout the region, extremes in wet and dry periods are expected to become more extreme.

  The shrimp industry within the tropical Pacific is likely to be sensitive to changes in rainfall patterns. The severe drought in New Caledonia from 1991 to 1995

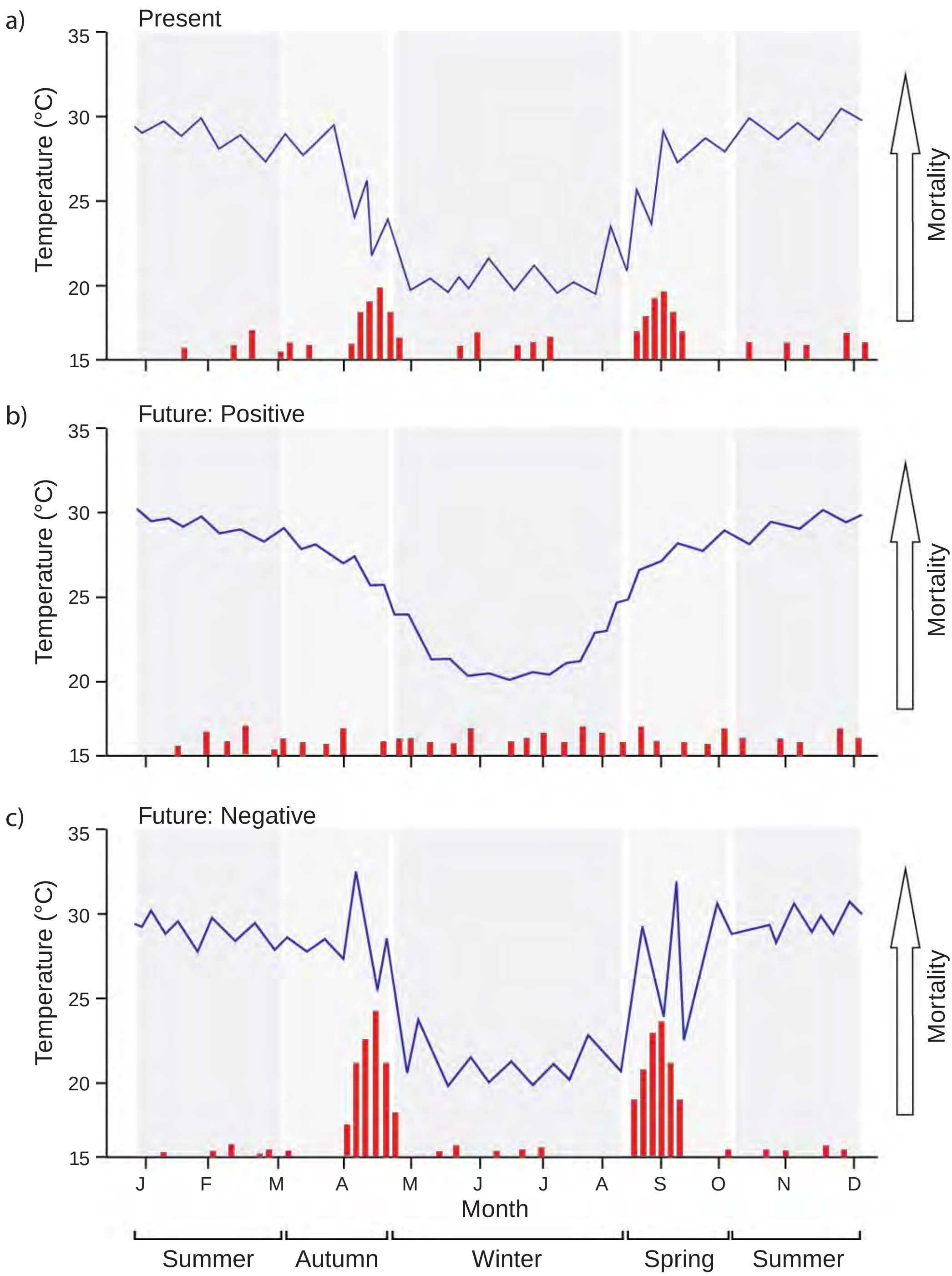


Figure 11.6 (a) Generalised rates of mortality (red columns) of the blue shrimp *Litopenaeus stylirostris* in ponds in New Caledonia throughout the year due to outbreaks of 'Summer Syndrome' and 'Syndrome 93' in autumn and spring; (b) expected decreases in mortality of shrimp if global warming reduces temperature variation in autumn and spring; and (c) projected increases in shrimp mortality if warming increases variation in temperature.

resulted in a significant increase in salinity and a decrease in mean temperature of ponds[176]. Sustained hypersaline conditions reduce the growth rate of *L. stylirostris*, and salinities > 55 PSU lead to high mortalities[61]. The largest shrimp farming company in New Caledonia recorded a 20% decrease in net yields from 1991 to 1995, attributed partly to the effect of the drought.

Extreme rainfall events can transport high quantities of minerals and organic nutrients into ponds through leaching from surrounding areas, depending on land use. Such events result in poor water quality in ponds (e.g. low dissolved oxygen levels) and unfavourable conditions for shrimp farming.

The increase in rainfall projected for Fiji is expected to hinder drying of ponds between production cycles – ponds must be thoroughly dried and the soil tilled to re-oxygenate it, before re-filling for the next culture cycle. Failure to do this stresses shrimp because of the toxic effects of inorganic nitrogen, resulting in greater risks of disease and catastrophically low harvests.

- **Ocean acidification:** Like some other crustaceans, penaeid shrimp typically exert high biological control over calcification by gradually accumulating intracellular stocks of carbonate ions to harden their chitin and protein exoskeletons, usually in the less soluble form of calcite. Therefore, formation of the exoskeleton in shrimp is not highly sensitive to the projected reductions in calcium carbonate ($CaCO_3$) expected to result from acidification of the ocean (Chapter 3).

  Litopenaeus stylirostris may be more sensitive to acidification of sea water than other species of penaeid shrimp, however, because of its thinner shell. Given the detrimental effects of marks such as 'black spot' on the price received for shrimp by farmers in New Caledonia, any deformities due to the effects of ocean acidification on thin shells would be expected to reduce profits. On the other hand, some crustaceans actually increase calcification when concentrations of carbon dioxide (CO_2) in sea water are high[177]. Research is required to determine if this is the case for *L. stylirostris* and *P. monodon*.

- **Sea-level rise:** The projected rises in sea level, described in Section 11.3.2.2 and in Chapter 3, are expected to cause major problems for the shrimp industry because farming operations depend on the ability to drain ponds quickly and effectively.

  Sea-level rise threatens the drainage of ponds because (1) the height differential between the pond floor and nearby coastal waters is reduced; and (2) mangroves and other aquatic vegetation are projected to migrate landward (Chapter 6), increasing the retention of sediment 'downstream' from shrimp farms and reducing the height differential further (**Figure 11.7**). Greater intrusion of salt water is also likely to promote colonisation of the channels that drain shrimp ponds by *Rhizophora* spp. (red mangrove), retarding flow.

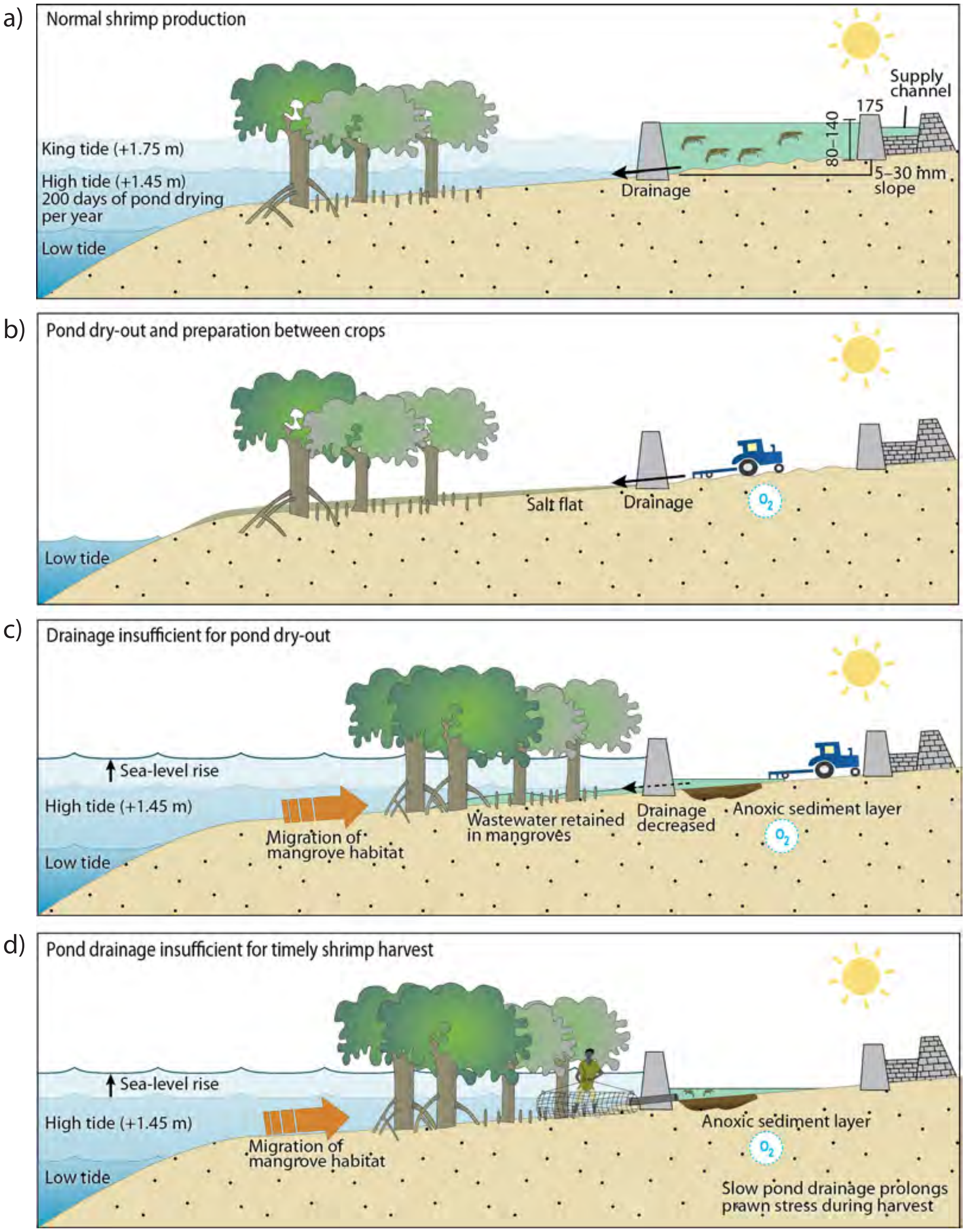


Figure 11.7 Present-day relationships of shrimp ponds in New Caledonia to the existing tidal levels when (a) shrimp are being grown throughout a normal production cycle, and (b) ponds are drained at low tide after harvest and dried between crops; and the adverse effects of sea-level rise and migration of mangroves on (c) drainage and drying of ponds between crops, and (d) the multiple partial-harvest system.

- **Cyclones:** If cyclones become more intense, greater levels of damage to shrimp ponds would be expected due to more powerful storm surges, and the scope for the waves to penetrate further inland due to sea-level rise. Shrimp farms in Fiji are likely to be the most susceptible to increased damage from stronger cyclones.

Potential impact and adaptive capacity

There are two main possible impacts of the projected rises in surface air temperature and SST on the shrimp industry in New Caledonia, depending on whether the autumn and spring seasonal temperature transitions become smoother, or more variable. Increases in pond temperatures, combined with reduced variation in temperature, during April and May (similar to the present-day conditions in Vanuatu) would benefit the production of *L. stylirostris* (**Figure 11.6b**). In particular, the growing season would be extended, perhaps enabling two production cycles per year, if conditions during summer do not become too hot. On the other hand, if climate change exacerbates variations in temperature during autumn and spring, which might occur if the land mass of New Caledonia has a 'continental effect', high losses due to vibriosis would be expected to continue (**Figure 11.6c**).

On balance, we expect the projected warming to reduce the effects of cold seasons on shrimp in New Caledonia, resulting in greater yields per hectare in 2035 compared with 2100. In particular, *L. stylirostris* would be expected to have faster growth rates under adequate management if climate change increases primary and secondary production levels in the semi-intensive ponds[178].

The warming conditions are also expected to increase the efficiency of farming *P. monodon* in Fiji. However, by 2100 the warming expected around New Caledonia and Vanuatu is likely to reduce growth rates of *L. stylirostris* during summer, particularly in Vanuatu. The projected warming could also preclude the option of stocking ponds with postlarvae at that time of year.

For *L. stylirostris* broodstock held in earthen ponds, there is also the possibility that the warmer conditions will increase the percentage of males with unviable sperm. To provide the postlarvae needed to capitalise on any opportunities for greater pond production resulting from the warmer conditions, shrimp farming enterprises may need to invest in indoor temperature-controlled facilities for maintaining broodstock.

If pond temperatures become untenable for producing *L. stylirostris*, the warming climate itself may provide the shrimp industry with an adaptation – producers in New Caledonia and Vanuatu may be able to diversify into warmer-water species, such as *P. monodon*. In Fiji, yields of *P. monodon* would be expected to increase under the warmer conditions but farmers there may also be able to consider growing the indigenous *P. semisulcatus* and *P. merguiensis*, provided that production methods are competitive with imported shrimp.

An increase in the frequency and intensity of drought events is expected to have a negative impact on yields from shrimp aquaculture in New Caledonia.

The effects of sea-level rise on the drainage of shrimp ponds is expected to have an adverse effect on the farming of *L. stylirostris* in New Caledonia and *P. monodon* in Fiji. However, in Fiji, ponds for the more-intensive culture of *P. monodon* are generally smaller and constructed at higher elevations than in New Caledonia, so that the impact of sea-level rise is expected to be lower.

The three main effects of sea-level rise on shrimp ponds (inhibiting outflow of wastewater, inability to lower pond levels quickly for harvesting, and loss of capacity to prepare emptied ponds before restocking) (**Figure 11.7**) could potentially have a powerful impact on the profitability of shrimp farming. Reduced ability to lower pond level quickly would also put at risk the current multiple partial-harvest system of pond management, by prolonging stressful crowded harvest conditions and leading to shrimp mortality or loss of product quality. Where farms are located in confined bays, poor drainage will increase the risk that effluents from ponds contaminate the water pumped to fill ponds. The potential problems are expected to be particularly severe in New Caledonia, where the ponds are typically built at the rear of mangrove areas in the intertidal zone (**Figure 11.8**). The problems are likely to affect the 8–12 ha ponds used for semi-intensive farming (stocked with 15–20 postlarvae per m^2), the 3–5 ha ponds farmed intensively (30–40 postlarvae per m^2), and the 0.2–0.4 ha ponds used to keep broodstock.

In New Caledonia, shrimp farmers will eventually face the expense of constructing new ponds at higher elevation or modifying existing ponds to improve drainage. Construction of new ponds will involve more intensive farming methods (higher stocking density, higher inputs) to compensate for the fact that fewer areas are expected to be suitable for shrimp farming. New approaches to shrimp farming will be needed. There are strong messages here for other PICTs considering the development of shrimp farming – farm layout and farming methods should be based on smaller ponds stocked at higher densities, built in more landward locations (**Figure 11.8**).

Adaptation based on modifying existing ponds will need to focus on heightening walls and raising the floor level of ponds to maintain water depth and the necessary height differential for rapid drainage[179]. The rate of sea-level rise is expected to be sufficiently slow to allow work on the heightening of walls to be done at the same time as routine maintenance.

Care will be needed in selecting the appropriate substrate for raising the floor level of ponds. Organisms associated with pond sediments comprise an important part of the diet of cultured shrimp[180–182], even when postlarvae are stocked at densities > 30 per m^2. Typically, the abundance of benthic meiofauna (copepods, nematodes, foraminiferans) in ponds falls by 85% during the first month after stocking shrimp[183]. However, rapid turnover of meiofauna ensures that they continue to contribute to

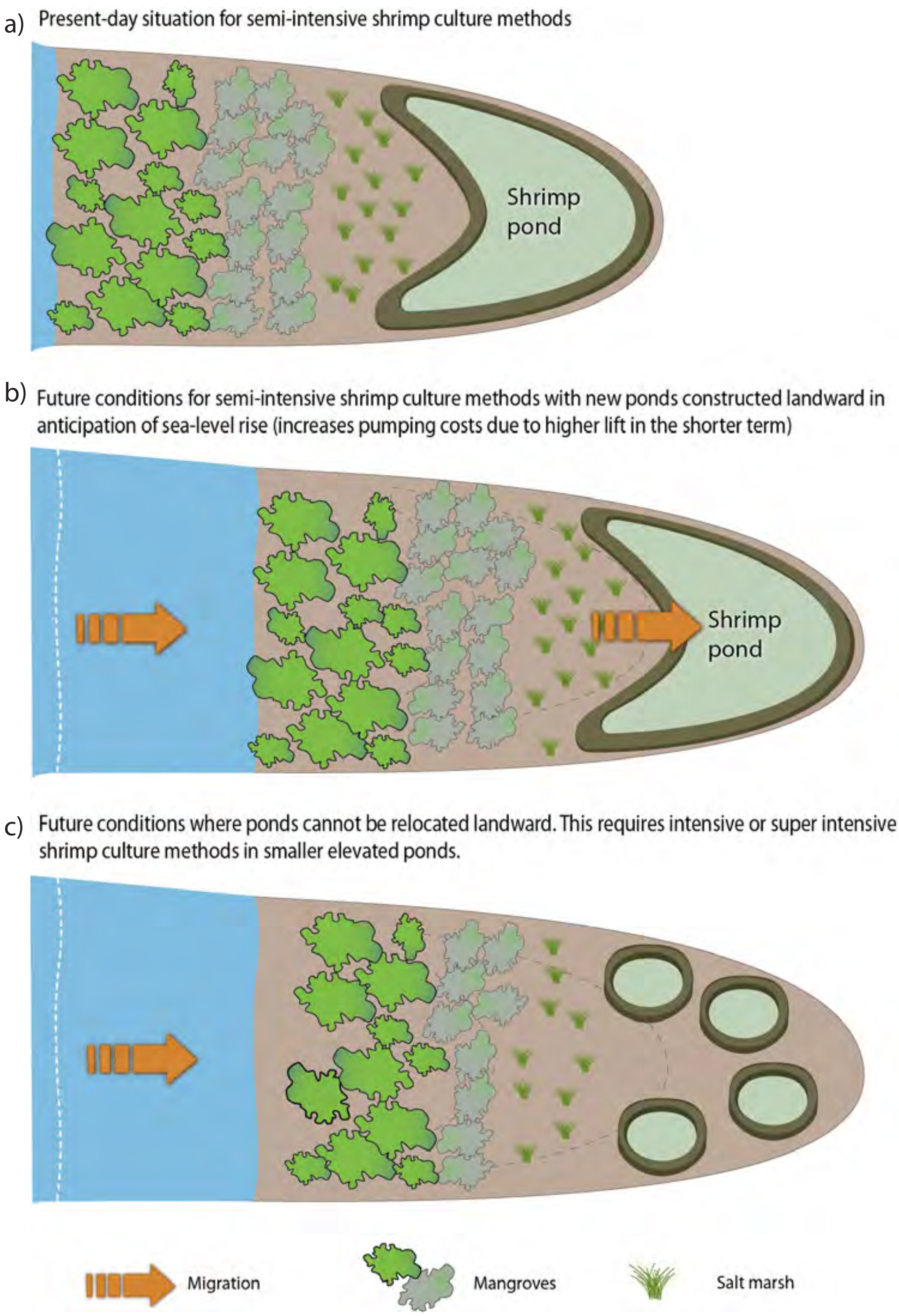


Figure 11.8 (a) Present-day relationships between intertidal coastal vegetation and semi-intensive shrimp ponds in New Caledonia; (b) relocation of semi-intensive shrimp ponds landward as sea level rises and coastal vegetation migrates; and (c) conversion of semi-intensive shrimp ponds to elevated, smaller intensive ponds as sea level rises where landward extension of ponds is blocked.

the nutrition and health of farmed shrimp. Boosting production of meiofauna by fertilisation can lead to significant gains in shrimp growth[183]. To retain these benefits, sediments suitable for colonisation by meiofauna should be used to raise pond floors.

Any adverse effects of seawater acidification on farmed shrimp can be partially addressed by application of agricultural lime during the preparation of ponds, although this will further increase production costs.

Shrimp farming in the tropical Pacific also needs to position itself to adapt to the effects of global warming on two of the key ingredients in the diet of cultured shrimp: *Artemia* and fishmeal. The larval rearing and acclimatisation of *L. stylirostris* in New Caledonia depends on large quantities of *Artemia* cysts (15 kg per million postlarvae), almost all of which (90%) are produced in Great Salt Lake, Utah, USA. However, *Artemia* cyst production in Utah drops significantly during El Niño events, which cause reductions in salinity and increases in temperature, as happened between 1993 and 1997[184,185]. Future supplies of *Artemia* can also be expected to be vulnerable to climate change. The shrimp industry in the region will need to switch to formulated micro-particles as soon as the promising research and development to produce this specialised food is complete.

Exposure to potential shortages of fishmeal is discussed in Section 11.3.2.1. Formulated diets fed to shrimp in ponds have a high fishmeal content (38–40% crude protein)[186] and can account for 35–40% of production costs[62]. Keeping pace with international trends in re-formulation of shrimp feeds to incorporate alternative sources of protein will be an important adaptation. Another key adaptation is to make better use of the natural productivity of ponds by rotating the farm through extensive or hyper-intensive modes, such as by development and application of biofloc technologies[187].

Subject to adaptive strategies being successful and cost-effective, it appears that the goal to double the production of the shrimp industry in New Caledonia to ~ 4000 tonnes per year, involving 1000 livelihoods, could still be met, assuming the industry can rise to existing socio-economic challenges to expansion and find appropriate niche markets for its product. Also, based on the likely future climatic conditions and amount of available space for shrimp farms, both Fiji and PNG should be able to retain their medium-term potential to produce 1000 and 2000 tonnes per year, respectively, employing about 500 people.

Vulnerability

The shrimp industries in New Caledonia and Fiji are estimated to have a low vulnerability under the B1 and A2 emissions scenarios in 2035. Indeed, climate change is expected to have a low, positive effect on production. In particular, the conditions for farming *P. monodon* in Fiji are likely to improve due to warmer pond temperatures. The prospect of increased temperatures resulting in improved yields of *L. stylirostris* in New Caledonia will depend on whether there is also reduction in the often rapid variation in temperature during autumn and spring, which can cause major losses of shrimp due to vibriosis.

By 2100, however, the outlook may not be as positive. Furthermore, the complexities of shrimp farming mean that the various aspects of the industry are likely to have differing vulnerabilities to climate change. For example, the survival and growth of the shrimp themselves are expected to be most vulnerable to changes in water temperature, whereas the profitability of farming operations has added vulnerabilities related to changes in rainfall patterns and sea-level rise. Any benefits due to faster growth rates of *L. stylirostris* in New Caledonia are likely to be eroded by (1) the costs involved in adapting the location or structure of shrimp ponds to overcome the effects of sea-level rise on the drainage of ponds; and (2) more extreme dry periods. Overall, shrimp production in New Caledonia is estimated to have low vulnerability to climate change under the B1 scenario in 2100, and low to moderate vulnerability under A2 in 2100.

11.3.2.3 Seaweed

Exposure and sensitivity

- **Temperature:** The projected increases in SST described in Section 11.3.3.1 represent considerable exposure for the seaweed *Kappaphycus alvarezii* farmed in the tropical Pacific. It is already at the upper limits of its temperature tolerance in the lagoons where it is grown in Kiribati, Fiji and Solomon Islands[188]. Indeed, recent increases in temperature that caused bleaching and mortality of corals (Chapter 5) were also detrimental for seaweed cultivation[68,189]. In particular, SST > 30°C inhibits growth, causes stress of *K. alvarezii*[68,190] and makes the seaweed susceptible to outbreaks of epiphytic filamentous algae, e.g. *Neosiphonia*, and tissue necrosis ('ice-ice'), resulting in stunting of plants and high mortalities (**Figure 11.9**). Seasonally rapid increases and decreases in temperature and salinity are also known to trigger such outbreaks[191].

  The species of harvested seaweed in Tonga, *Cladosiphon* sp. (mozuku), is also expected to be sensitive to increased SST because it relies upon marked seasonal changes in temperature for annual sporulation and completion of its life cycle. Warmer SSTs are likely to inhibit reproduction and growth of this species.

- **Rainfall:** Seaweed farming operations in tropical areas are expected to be exposed to significant increases in rainfall (Section 11.3.2.1, Chapter 2). *Kappaphycus* is sensitive to reduced salinities and the farming of this seaweed is already limited to areas well away from the influence of runoff[68].

- **Ocean acidification:** The higher projected concentrations of dissolved CO_2 driving the expected decreases in the pH of the ocean (Chapter 3) are likely to stimulate the growth of seaweed. Like all plants, *K. alvarezii* depends on CO_2 for photosynthesis and might be expected to have a faster growth rate as the concentrations of CO_2 in the ocean increase, if other variables remain constant. As described above, however, other features of the environment are likely to retard growth, so any potential benefit to seaweed farming from the higher levels of dissolved CO_2 is questionable unless farming operations can be moved to better locations.

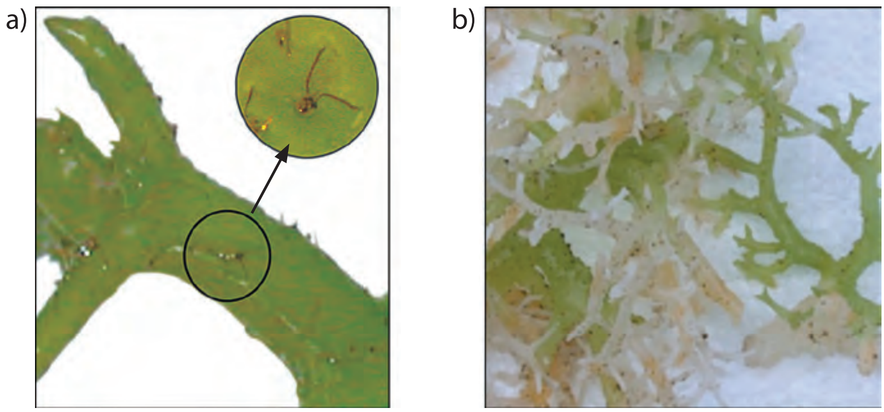


Figure 11.9 Farmed seaweed *Kappaphycus alvarezii* affected by (a) epiphytic filamentous algae, and (b) tissue necrosis (photos: Reuben Sulu).

- **Sea-level rise:** Seaweed farming is also heavily exposed to the projected increases in sea level described in Section 11.3.3.1 and Chapter 3 because the activities occur in shallow subtidal areas. While this may result in some locations no longer being suitable for seaweed farming due to an increase in depth, the increase in local currents associated with sea-level rise is expected to benefit seaweed farming. Indeed, successful production of *K. alvarezii* depends on water movement[189,192].

  The main advantage of stronger currents is that they help overcome shortages of nitrogen, caused by low rates of water exchange in combination with other stresses, such as higher temperatures or lower salinities, which result in outbreaks of ice-ice and epiphytic filamentous algae. However, good growth can be achieved in oligotrophic conditions where strong water movement increases nutrient flux. For this reason, *K. alvarezii* is farmed most often on the back-reef coralline-sand flats of high island lagoons, or on coralline-sand flats adjacent to inhabited islets in the lagoons of atolls, where there is sufficient water exchange to support 'off-bottom' (wooden-stake) culture.

- **Cyclones and ENSO events:** In Fiji, seaweed farming may possibly be exposed to more intense cyclones. However, because seaweed farming is sensitive to the effects of waves generated by winds of much lower velocity than those typical of cyclones, it is no more sensitive to more intense cyclones than it is to present-day cyclones – both can be expected to destroy stocks of plants and infrastructure. The sensitivity of seaweed farming to wind strength and direction is demonstrated by responses to ENSO events. In Kiribati, the reversal in wind direction that occurs during El Niño episodes sets up harmful wave action in seaweed farming sites that are normally sheltered (**Figure 11.10**), requiring shifts in farm locations. Such changes in wind direction are expected to continue, although there is no consensus on future changes to the frequency or intensity of ENSO events (Chapter 2).

Potential impact and adaptive capacity

The projected increases in SST pose a significant threat to seaweed farming in Solomon Islands and Kiribati. By 2100, the areas for growing seaweed in these countries are expected to be above the upper thermal limit for present varieties of *K. alvarezii* for most of the year, reducing production substantially and increasing susceptibility to disease. Under the A2 scenario, many sites where production of seaweed is underway today may become unsuitable for farming. This applies less to Fiji, where coastal waters are cooler than in Solomon Islands. However, even there, SST is expected to be above the upper thermal limits for part of the year by 2100, threatening the viability of seaweed farming.

The impact of higher SST may be reduced in locations where rising sea level causes increased over-topping of reefs by ocean swells, leading to increased current velocity, shorter residence times of sea water in enclosed lagoons and lower water temperatures. Such changes would be expected to help maintain seaweed production unless the stronger tidal currents and wave action resulted in loss of plants or damage to equipment. The projected degradation of coral reefs due to climate change (Chapter 5) may increase the locations where currents can penetrate to seaweed growing areas.

At sites where currents remain within acceptable limits, the problems caused by higher SST are likely to be compounded by increased rainfall, leading to more regular losses of seaweed from ice-ice and epiphytic filamentous algae. These incidents will have a strong local impact because production cannot recommence until farms can be restocked by propagating seaweed cuttings delivered from unaffected localities.

There is limited scope for adaptation of seaweed farming at the regional level by shifting production to higher latitudes – it is an activity suited only to remote coastal communities in countries with low expectations of return on labour, and where there are few alternative opportunities to earn income. In principle, it could be expanded to Vanuatu as temperatures warm, but considerable research would be needed to assess the suitability of sites and the social need for, and acceptance of, seaweed farming.

There is no scope for selection of temperature-tolerant strains unless new varieties of *K. alvarezii* are imported, because all seaweed cuttings in the region are vegetatively-propagated clones derived from small founder stocks imported from Southeast Asia.

In the absence of new, more temperature-tolerant varieties, strategies for growing the existing stock will need to be devised to reduce the effects of climate change on production, and to increase the speed of recovery of yields after disruptions.

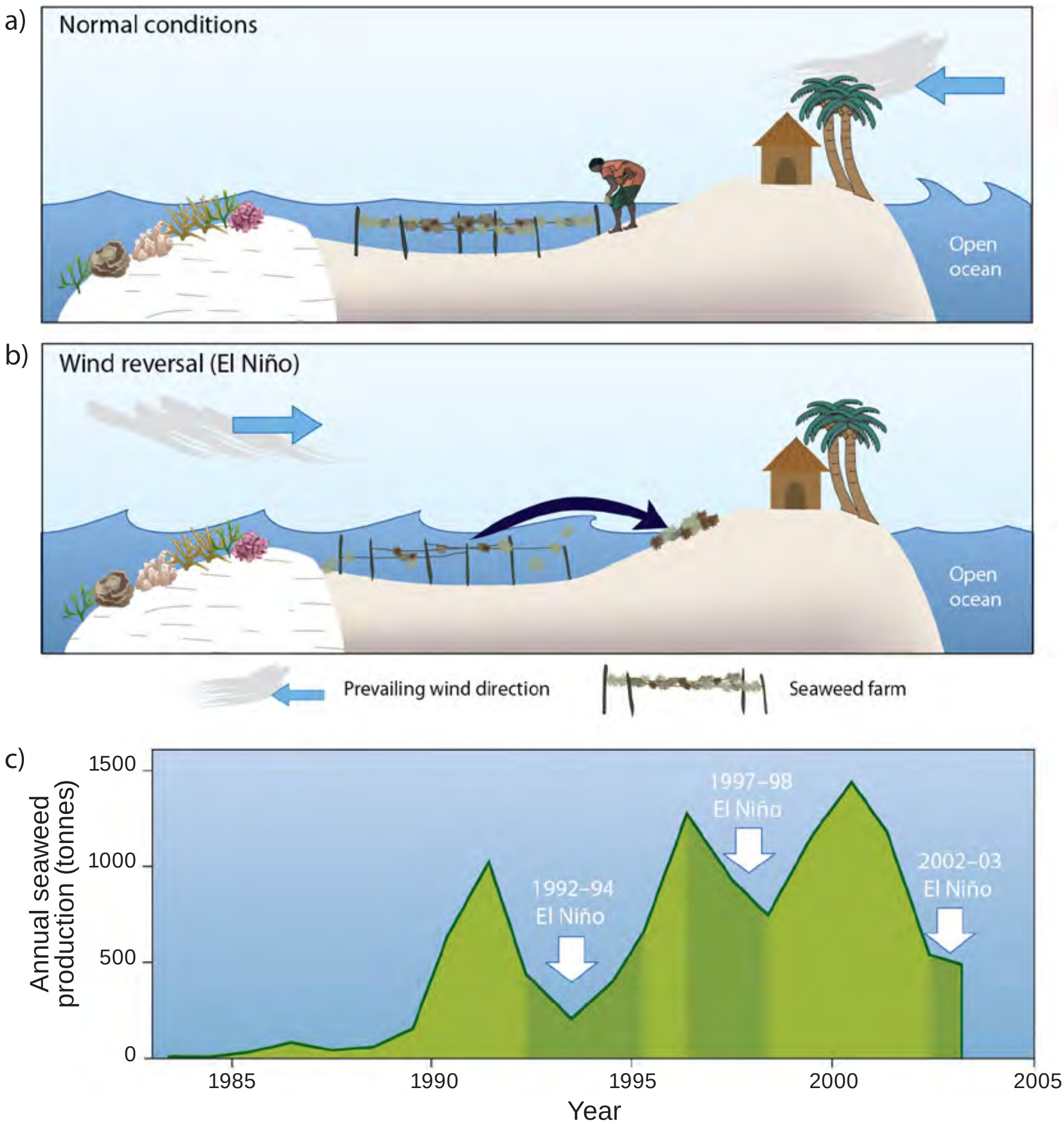


Figure 11.10 (a) Average conditions for farming seaweed in Kiribati, (b) effects of altered wind conditions associated with El Niño events on seaweed farming in Kiribati, and (c) consequences of El Niño events for total annual seaweed production in Kiribati.

Sites where temperatures and salinities are likely to be suitable for growing seaweed need to be identified for existing production areas in Kiribati, Solomon Islands and Fiji, with a view to re-location of operations away from sites where conditions deteriorate. The key to this will be finding locations where currents regularly flush prospective farming areas. In the shorter term, seaweed at such sites may benefit from the increasing concentrations of CO_2 in the ocean. However, restrictions are expected on the length of time seaweed can be grown at any site due to the increasingly adverse effects of higher SST and rainfall. Thus, seaweed farming should be regarded as a shorter-term investment opportunity. As harvests of seaweed become more unreliable, due to regular outbreaks of ice-ice and epiphytic filamentous algae, seaweed farmers will need assistance to diversify into other livelihoods.

Increases in SST are expected to reduce the viability of *Cladosiphon* aquaculture because farming systems are dependent on availability of natural sporefall.

Vulnerability

Farming of *Kappaphycus* seaweed in the tropical Pacific is estimated to have a moderate vulnerability to climate change by 2035 under the B1 and A2 emissions scenarios. By 2100, this form of aquaculture is likely to have moderate to high vulnerability under B1, increasing to high vulnerability under A2. Continued selection of more suitable farming sites and introduction of a more suitable seaweed variety will be required to reduce the vulnerability of seaweed culture. Production targets of 1000–2000 tonnes per year for both Fiji and Solomon Islands should still be achievable until 2035, but not necessarily in the same places or using the existing methods of management.

11.3.2.4 Marine ornamentals

Exposure and sensitivity

- **Temperature:** Because coral fragments cultured for the aquarium trade are grown in shallow, sheltered coastal areas (**Figure 11.11**), their exposure to increasing SST is expected to be as high as, or higher than, the exposure of coral reefs described in Chapter 5. The major response of corals to increased SST is expulsion of their zooxanthellae, which affects their energy production, potentially reducing growth and ultimately resulting in the death of colonies after protracted bleaching[193–195] (Chapter 5).

  The projected steady increase in SST under the B1 and A2 emissions scenarios of 0.5–1.0°C by 2035, is expected to cause coral fragments to bleach twice as frequently as today (Chapter 5). The increased levels of temperature stress by 2035 are likely to result in a 25% increase in loss of coral fragments relative to 2007, particularly in the case of branching species such as *Acropora* and *Stylophora* (Chapter 5). Under the B1 scenario by 2100, coral bleaching is projected to occur every 1–2 years and most branching species are expected to be too difficult to grow, although it may still be possible to culture fragments of massive species such as *Porites*, and encrusting corals like *Favia* and *Favites* (Chapter 5). Under A2 by 2100, SST is expected to be hostile to most species of corals, except very robust extremophiles.

The giant clams cultured for the ornamental trade also rely on zooxanthellae within their mantle tissue to supply organic compounds needed for growth[78,196]. The zooxanthellae are expelled from the mantle during periods of unusually warm SST[200,201]. Prolonged periods of bleaching can result in mortality of giant clams because, although they obtain a proportion of their food by filter feeding[196], they do not survive when deprived of sunlight and the products of photosynthesis by zooxanthellae. Lethal temperatures for giant clams are ~ 34–35°C[77,197]. Below the temperature threshold that induces bleaching, growth of giant clams is correlated positively with SST[75].

Increasing SST is also expected to alter the abundance and distribution of postlarval fish and crustaceans through changes in spawning location and duration, and the effects of higher temperatures on larval dispersal and survival[198] (Chapter 9). However, little is known about the sensitivity of the species presently collected in 'capture and culture' operations to changes in SST.

Figure 11.11 Coral fragments grown on trellises in sheltered, shallow coral reef habitats in Solomon Islands (photo: Jamie Oliver).

- **Rainfall:** The projected increases in rainfall in tropical areas (Section 11.3.2.1, Chapter 2) are expected to have advantages and disadvantages for enterprises culturing corals and giant clams in sheltered coastal waters. In locations where there are modest increases in runoff, the additional nutrients are likely to boost the growth rates of corals and giant clams, provided any associated increase in turbidity does not unduly inhibit photosynthesis by zooxanthellae[199,204]. Where salinities drop to 25–30 PSU for short periods, the growth of corals[202] and giant clams is unlikely to be affected. However, where the volume and duration of runoff increases significantly due to more extreme rainfall, conditions are expected to be unsuitable more often for culturing corals and giant clams due to (1) the adverse effects of prolonged reductions in salinity and light; and (2) the effects of increases in sedimentation and fouling by epiphytic algae and macroalgae[202–204](Chapter 5).

Cultured corals and giant clams are unlikely to be sensitive to any reduction in nutrients in coastal waters due to increased stratification resulting from projected changes in salinity and SST (Chapter 3) because they receive much of their nutrition from the organic products of photosynthesis by zooxanthellae.

- **Ocean acidification:** Corals farmed for the ornamental market will be exposed to the effects of ocean acidification on aragonite saturation levels in the same way as natural coral reefs (Chapter 5). By 2035, calcification of coral colonies is likely to be 50% less than that seen in the early 1990s. In 2100 under the B1 scenario, reef calcification is expected to be reduced by ~ 80%, and physical and biological erosion is likely to exceed calcification. The situation is likely to deteriorate further under A2 in 2100, when atmospheric CO_2 is expected to surpass 750 ppm, driving ocean pH below 7.7 and carbonate ion concentrations far below the levels needed for coral growth (Chapter 5).

  Ocean acidification is also likely to affect the culture of giant clams and the crustose coralline algae components of live rock. Acidification is expected to result in reduced growth and weaker valves in giant clams because their shells are made of aragonite[177]. Crustose coralline algae are likely to be susceptible to the effects of acidification earlier than corals because these algae secrete high levels of magnesium calcite, which is more soluble than the aragonite of coral skeletons[205]. Thus, crustose coralline algae are also expected to be in danger of dissolution rates exceeding calcification rates by the end of this century[206]. Enterprises producing live rock depend on their products being ready to sell within 6 to 12 months. Even then, operations are only marginally profitable and recent research aims to reduce production times[207]. These enterprises are expected to be susceptible to any delays in production of live rock due to slower calcification rates.

  Ocean acidification is also expected to alter the recruitment success of postlarval fish and invertebrates, through changes to their fitness and behaviour[153–156] (Chapter 9), and the marine food webs that support them[208,209] (Chapter 4).

- **Sea-level rise:** The projected rises in sea level (Section 11.3.2.1) are expected to increase rates of water exchange in atoll lagoons, and some inshore habitats around high islands, through increased over-topping of reefs by ocean swells. Village-based enterprises producing cultured coral fragments and giant clams for the aquarium trade are expected to have access to more potential grow-out sites as water circulation and nutrient supply at previously oligotrophic areas increase, along with sea level.

- **Cyclones:** The possibility that cyclones may become more intense, but less frequent (Chapter 2), may not necessarily increase the sensitivity of farmed marine ornamental products or the infrastructure required – any cyclone is likely to destroy equipment and stock left in shallow water. A reduction in frequency of cyclones would be expected to reduce such losses.

- **Habitat alteration:** As described above and in Chapter 5, global warming and ocean acidification are expected to degrade coral reefs progressively. Consequently, there are expected to be fewer sources of coral fragments for grow-out, particularly for branching coral species. It remains to be seen whether degradation of coral reefs reduces the supply of giant clam broodstock – the two most popular species in the ornamental trade, *Tridacna maxima* and *T. crocea*, also occur in dead, massive corals.

Potential impact and adaptive capacity

The combined effects of projected changes to SST, rainfall, ocean acidification, sea-level rise, cyclones and coral reef habitats in 2035 are expected to have a low potential impact on enterprises farming corals and giant clams in the shallow coastal waters of the tropical Pacific. In fact, although more bleaching is predicted to occur, the time required to grow these products to market size is expected to be reduced under the warmer and more nutrient-rich conditions in countries such as Vanuatu and Tonga. By 2035, warming is also likely to benefit flow-through giant clam hatcheries in Vanuatu, by making spawning and larval rearing possible year-round. Farm sites can be chosen in areas where the occurrence of bleaching is low, such as resilient areas of lagoons, or simply by moving the farms deeper.

Coral bleaching

Photo: Ove Hoegh-Guldberg

By 2100, medium to high negative effects on farm production caused by regular bleaching are likely. Similarly, corals and giant clams are expected to have difficulty forming their skeletons and shells due to increased acidification of the ocean and the detrimental effects of increased runoff. These problems are projected to emerge earlier for the branching corals that dominate the trade in coral fragments. Production of live rock is expected to become unprofitable in many areas during the second half of the 21st century.

It is difficult to see how enterprises producing corals and giant clams in equatorial areas will be able to adapt, because transferring operations from the sea to recirculating tanks on land, where they could control water temperature and pH, requires seawater pumping and acquisition of land-based sites. Such costs would place these enterprises at a competitive disadvantage to those in subtropical areas. Growth rates of giant clams in re-circulation systems can, however, be maximised by fine-tuning the addition of nutrients[199], and shading to enhance mantle colour[210], assisting growers to obtain higher prices.

As coral reefs degrade, coral farmers who depend on collection of fragments from the wild will need to progressively transfer production from branching species, to massive and encrusting species, and develop markets for these products. Fragments of branching corals will probably need to be supplied from source colonies held under controlled conditions in land-based facilities.

Where it is still possible to produce corals, giant clams and live rock in the sea, e.g. micro-sites at higher latitudes with suitable levels of aragonite saturation (Section 11.3.3.1), provision will need to be made to move stock ashore, or to much deeper water, before the onset of cyclones and storms.

The potential impacts of the projected environmental changes on the capture and culture of postlarvae is difficult to identify – the industry is based on a broad range of species but focuses on those that cannot be collected easily as adults. It is possible that a different but equally valuable ‘scarce’ suite of postlarvae may be available to harvest and grow under a changing climate.

Vulnerability

The broad range of marine ornamental products is expected to have differing vulnerabilities to climate change and acidification of the ocean. The changing environment is likely to have low, negative effects on the production of cultured corals and giant clams under the B1 and A2 emissions scenarios in 2035. However, enterprises growing these two products in shallow coastal habitats are likely to have moderate to high vulnerability to the changes projected to occur by 2100 unless they can find economical ways of developing land-based systems that ease the stress likely to be caused by higher SST and ocean acidification. The vulnerability of live rock producers is also expected to be moderate in 2035, increasing to high by 2100. It is not possible to determine the vulnerability of postlarval capture and culture operations, but it may be low.

11.3.2.5 Freshwater prawns

Exposure and sensitivity

- **Temperature:** Aquaculture of the introduced *Macrobrachium rosenbergii* occurs in the same general type of earthen freshwater ponds used for tilapia (Section 11.3.2.1) and is exposed to the same projected increases in water temperature relative to 1980–1999: 0.5–1.0°C for B1 and A2 in 2035, 1.0–1.5°C for B1 in 2100 and 2.5–3.0°C for A2 in 2100. The optimum temperature range for *M. rosenbergii* is 26–32°C and they become stressed below 22°C or above 34°C[82,211,212]. Freshwater prawns are less tolerant of temperature stresses than tilapia but more resilient than penaeid shrimp. Little is known about the temperature tolerances of the indigenous freshwaters prawns *M. lar*, apart from some observations reported by hobbyists which indicate a preferred range of 23–28°C. Occurrence of *M. lar* in montane river habitats (Chapter 7) indicates that this species may indeed have a lower preferred temperature range than *M. rosenbergii*.
- **Rainfall:** Projected increases in rainfall mean that freshwater prawn farming enterprises are likely to be exposed to greater risk of flooding, and more extreme rainfall events (Section 11.3.2.1, Chapter 2). Farming operations are sensitive to flooding because prawns escape when rising waters over-top or damage pond walls.
- **Sea-level rise:** Intrusion of saline water further inland (Chapter 3) is not expected to have a major impact on grow-out of *M. rosenbergii*, because it grows well in water of 5 PSU although survival decreases if salinity exceeds 10 PSU[213].
- **Cyclones:** Floods caused by more intense cyclones have the potential to damage ponds constructed for freshwater prawns. Such floods would also increase the risk of prawns escaping from ponds.
- **Habitat alteration:** The projected increased rainfall is expected to expand freshwater habitats in the tropical Pacific by up to 10% in 2035 and 20% in 2100 (Chapter 7). In turn, the greater availability of habitat is expected to augment production of freshwater fish and invertebrates in most PICTs by up to 2.5% in 2035, by 2.5–7.5% for B1 in 2100, and by 2.5–12.5% for A2 in 2100 (Chapter 10), where catchments are well managed. Because *M. lar* is a conspicuous part of the freshwater fauna in lowland areas, the abundance of wild juveniles is also likely to increase in line with these estimates.

Potential impact and adaptive capacity

The warming projected to occur by 2035 is not likely to adversely affect aquaculture of freshwater prawns in the tropical Pacific. Rather, the expected range of temperatures is likely to increase their rates of growth and survival. However, by 2100 warming in equatorial regions could result in pond temperatures in excess of 34°C at some times of year, and losses of production through increased stratification and heat stress. A more positive possible outcome by 2100 is that the warming temperatures could make culture of *M. rosenbergii* practical in subtropical areas.

The projected increases in rainfall should increase availability of fresh water and provide opportunities to farm *Macrobrachium* spp. in a greater range of locations. The possibility of a greater abundance of *M. lar* would make it easier to collect wild juveniles for grow-out operations. *Macrobrachium lar* also has the advantage that it is hardier than *M. rosenbergii*, and expected to be more resilient to stressful environmental conditions.

Adaptations to reduce the eventual adverse effects of warmer pond temperatures centre around locating and constructing ponds to create high rates of water turnover in the way described for tilapia and carp in Section 11.3.2.1, particularly as freshwater prawns do not directly rely on plankton blooms.

Future developments to capitalise on the potential of this commodity should be based on semi-intensive production to avoid creating the kind of host-pathogen-environment interactions that lead to disease and production losses (Section 11.3.4).

Although the protein requirements of *Macrobrachium* spp. are less than for penaeid shrimp, commercial enterprises will still depend on some fishmeal to formulate suitable diets. Thus, any effects of climate change on the global supply of fishmeal are likely to increase production costs. Freshwater prawn farmers could adapt by using fishmeal from the increased number of tuna canneries in the region (Chapter 12). Alternatively, any freshwater prawn farming enterprises established near major rivers in PNG could arrange with local fishers to use the unwanted introduced species common there (Chapter 10) to make local supplies of fishmeal. *Macrobrachium lar* appears to have lower dietary protein requirements than *M. rosenbergii*, although this needs to be confirmed by more research.

Vulnerability

Freshwater prawn aquaculture does not appear to be particularly vulnerable to climate change because it is currently a fledgling industry. However, any development of freshwater prawn farming in PICTs with sufficient domestic market demand to support commercial enterprises is expected to benefit from a low, positive effect on production under the B1 and A2 emissions scenarios in 2035. This assessment changes for 2100, when freshwater prawn farming is expected to have a low vulnerability to climate change.

11.3.2.6 Marine fish

Exposure and sensitivity

- **Temperature:** The exposure and sensitivity of the limited number of hatchery-based marine fish aquaculture operations in the region (Section 11.2.2.6) to the projected changes in SST (Chapters 2 and 3) are expected to be low in 2035. These operations rely on captive broodstock and often use environmentally controlled facilities to mature them, and rear the progeny, to the point where the juveniles are ready to stock into sea cages. The exposure and sensitivity of marine fish held in sea cages to the projected increase in SST is likely to be similar to the responses of demersal fish associated with coastal habitats, i.e. metabolic rates are expected to increase (Chapter 9). Depending on the species and location of operations, growth could be inhibited under the A2 emissions scenario by 2100.

Collection of wild juvenile rabbitfish (**Figure 11.12**) for grow-out to supply local markets is expected to be sensitive to increases in SST. The timing of spawning, and the survival and distribution of larvae of rabbitfish, can be expected to respond to changes in water temperature to some extent, although how this may affect existing distribution patterns of postlarvae remains to be determined. Whatever the distribution, the already great interannual variation in abundance of juvenile rabbitfish[90] is projected to increase due to the effects of higher SST on larval development (Chapter 9).

Figure 11.12 Juvenile rabbitfish (Siganidae) which settle in coastal habitats in the western Pacific in high but variable numbers each year (photo: Antoine Teitelbaum).

- **Rainfall:** Marine fish farming operations are expected to have only minor sensitivity to the projected reduction in the salinity of coastal waters stemming from increases in rainfall (Chapter 2). Although both hatchery and grow-out sites require sheltered areas with salinities of ~ 35 PSU, and the number of such sites will be reduced in the future, there should still be sufficient suitable areas in those PICTs that decide to engage in marine fish farming.
- **Ocean acidification:** Hatchery-based marine fish aquaculture operations growing fish in sea cages are not expected to be adversely affected by the projected acidification of the ocean (Chapter 3) because the survival and growth of demersal fish do not appear to be affected by reductions in pH of 0.1–0.3 units (Chapter 9).

On the other hand, there is the possibility that enterprises based on the collection of wild juveniles may be jeopardised by increasing variability in the supply of juveniles if ocean acidification has an adverse effect on the behaviour of larvae[154–156] (Chapter 9).

- **Sea-level rise:** Development of marine fish farming is likely to have only minor exposure to the effects of increases in sea level. However, some of the protection presently offered by coastal habitats, e.g. coral reefs and mangroves, that help create the sheltered sites needed for sea cages, may be reduced as sea level rises.
- **Cyclones:** Sea cages, hatcheries and other infrastructure involved in marine fish farming are already exposed to severe damage by storm surges and strong winds in PICTs where cyclones occur. The degree of additional potential damage likely to occur during stronger cyclones is difficult to assess – any cyclone near a marine fish farming enterprise is likely to cause major problems.
- **Habitat alteration:** Because the broodstock for prospective species for hatchery-based fish farming are likely to survive, even if widespread degradation of coral reefs occurs (Chapter 9), few adverse affects are expected for this type of aquaculture through habitat alteration. As warmer SSTs and increased ocean acidification degrade coral reefs (Chapter 5), macroalgae, which form a major part of the diet of rabbitfish[214], are expected to proliferate. This food source may boost the supply of wild-caught juveniles for rabbitfish farming.

Potential impact and adaptive capacity

Climate change and ocean acidification are expected to have relatively minor impacts on any development of marine fish farming in the region. Such enterprises would need to make comprehensive assessments of the suitability of local environmental conditions for establishment of hatcheries and sea cages, and markets, before investment occurs. Thus, any effects of projected climate changes on prospective marine fish species, or the infrastructure needed to produce them, can be taken into account during that process. A possible longer-term effect is that once sites are selected, fish may need to be fed a greater daily ration due to their higher rates of metabolism in warmer waters.

With the exception of siganids, optimum diets for cultured marine fish have a high fishmeal content[215]. The same concerns about the broader global effects of climate change on supply of fishmeal, and the possible adaptations to cope with periodic shortfalls in supply described for tilapia farming (Section 11.3.2.1), also apply to marine fish but would be more pronounced.

Vulnerability

The vulnerability of existing and future marine fish aquaculture in the tropical Pacific to climate change and ocean acidification is expected to be low under the B1 and A2 emissions scenarios in 2035, and under B1 in 2100, possibly increasing to low to moderate in 2100 under A2.

11.3.2.7 Sea cucumbers

Exposure and sensitivity

- **Temperature:** Projected increases in surface air temperature and SST (Chapters 2 and 3) are expected to cause changes in the reproduction and growth of *H. scabra* (sandfish), which may influence the efficiency of farming this species in ponds, and release of cultured juveniles in restocking and sea ranching initiatives. Growth rates in ponds in Vietnam[96] are much faster than those in New Caledonia[102], indicating that greater rates of production from ponds should be possible for *H. scabra* in areas away from the equator as these regions warm. In equatorial areas, however, rising temperatures may result in longer periods near the upper thermal limit for sandfish and higher mortality during warm months. Survival of small juvenile sandfish is lower at temperatures > 32°C[103].

  Possible upper lethal temperature limits of larger sandfish are indicated by total mortality of adults in ponds exposed to water temperatures of 35°C during trials in northern Australia. However, stratification of the water column due to freshwater influx is likely to have contributed to the mortality, and low dissolved oxygen levels probably exacerbated the temperature effects.

  Reproduction of *H. scabra* is linked to temperature because spawning can be induced year round within 10–12°N/S of the equator, but only for 3–4 months in New Caledonia (22°S). Culture of larval sandfish and grow-out of juveniles is recommended when temperatures are between 26°C and 30°C[99,216,217]. Thus warmer conditions should assist hatchery production in Fiji, Vanuatu and New Caledonia.

  Cultured sandfish released into shallow seagrass beds in sea ranching projects are likely to be adversely affected by increasing SST. Sandfish > 40 mm reduce burying activity at 29°C[218,219], increasing the time they are at risk of predation[220].

- **Rainfall:** Although sandfish are tolerant of salinities as low as 20 PSU[110], the culture of sandfish in ponds is likely to be affected negatively by the projected increases in rainfall in the tropics (Chapter 2) because reduced salinities are likely to increase the risk of stratification, resulting in potentially lethal low levels of dissolved oxygen. Plans to produce sandfish in ponds in New Caledonia may not be threatened in this way because rainfall is projected to decrease in the subtropics (Chapter 2). Sea cucumber larvae appear to be less tolerant of low salinities than adults[221], although this is not expected to be a problem because salinities can be managed in hatcheries.

- **Ocean acidification:** There has been no research on the effects of projected ocean acidification (Chapter 3) on sandfish. However, research on other sea cucumbers, and related sea urchins and starfish, suggest that sandfish may have some sensitivity to reduced concentrations of carbonate ions in sea water. In particular, the size and strength of the calcareous spicules in the outer layer of their skin is likely to be reduced as acidification of the ocean increases. Developing larvae are also known to be sensitive to changes in pH, for reasons yet to be explained[221,222].

- **Sea-level rise:** Where sandfish are grown in existing shrimp ponds, the projected increases in sea level (Section 11.3.2.2, Chapter 3) are expected to create difficulties in draining ponds (Section 11.3.3.3). However, where ponds are dedicated to producing sandfish, complete drying of ponds between production cycles may not pose the same problems as for shrimp farming because few nitrogenous feeds are used to grow sandfish and the harvest does not depend on rapid drainage of ponds.

- **Cyclones:** Sea ranching operations, which involve releases of juvenile cultured sandfish into seagrass beds[103], are likely to be highly sensitive to the effects of cyclones. Occurrence of a cyclone between release of juveniles and harvest is likely to reduce yields significantly because the resulting turbidity and wave action would inhibit burying[218]. Storm surges could also displace sandfish to unsuitable habitats and cause abrasion of sandfish, increasing the risk of disease and mortality.

- **Habitat alteration:** The projected changes in the area and leaf density of seagrass beds, due to the expected increases in SST, runoff and possibly storm surge (Chapter 6), would alter the quality and extent of suitable sites for releasing sandfish in sea ranching projects. Survival of juvenile sandfish released in the wild is strongly related to the quality of the site[103] (**Figure 11.13**).

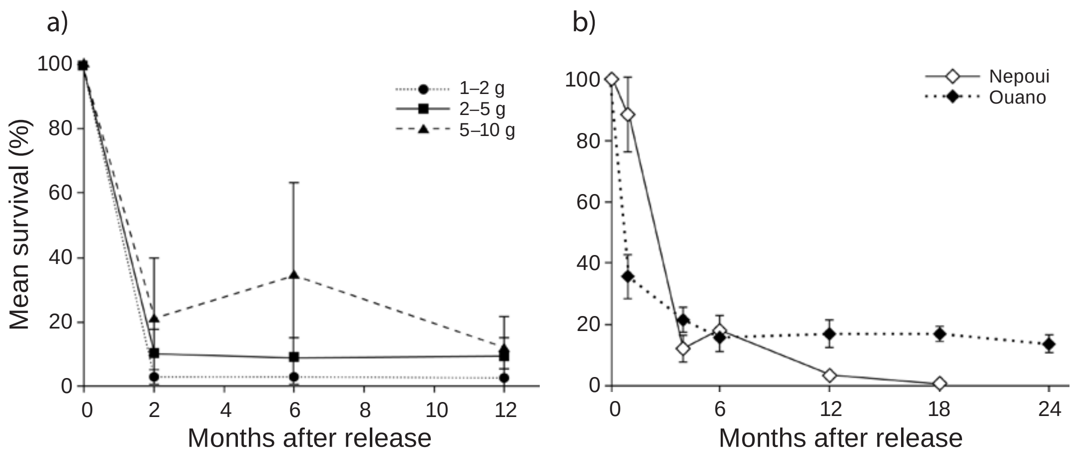


Figure 11.13 (a) Mean percentage survival of released juvenile cultured sandfish of different sizes after 12 months at two sites combined in New Caledonia; and (b) mean average survival of released juvenile cultured sandfish, weighing between 1 g and 20 g, after 24 months at two sites in New Caledonia; vertical bars are standard errors (source: Purcell and Simutoga 2008)[103].

Potential impact and adaptive capacity

The possible effects of climate change are expected to vary for the two most promising uses of hatchery-reared sandfish – sea ranching and farming in ponds. The warmer conditions are likely to enable juveniles to be produced in hatcheries year-round in more PICTs. On the other hand, hatchery production may be impeded by warmer conditions in equatorial areas. Similar considerations apply to growth and survival in ponds, and in sea ranching projects. Enterprises farming sandfish in ponds in subtropical areas are expected to benefit from faster growth rates with only modest risk of increased stratification of ponds. Conversely, without specialised management of ponds, sandfish in ponds in the tropics are likely to suffer high mortality due to the increased likelihood of stratification caused by higher rainfall and reduced salinity.

Higher water temperatures, reduced salinities and ocean acidification are expected to affect the success of sea ranching operations. In the tropics, higher SSTs and increased levels of runoff are projected to affect both the survival of sandfish and the quality of their seagrass habitats. In the subtropics, cyclones and storms will continue to pose the main climate-related direct and indirect risks to the profitability of sea ranching due to loss of juveniles and their seagrass habitats. Ocean acidification may reduce the fitness of released juveniles in both the tropics and subtropics, although further research is needed to assess the likelihood of this potential impact.

Adaptations can be made within hatcheries to control water quality, including temperature, salinity and pH, so no problems are anticipated in producing juvenile sandfish in the future. Methods have also been developed in Vietnam to avoid low salinities in ponds during the wet season. These methods include ensuring that pond stratification is avoided by mixing the water column during heavy rainfall, and maximising the turnover of sea water.

For sea ranching projects, careful selection of sites likely to maximise the survival of released juveniles will be an essential way of adapting to the changing environmental conditions. However, it may also be possible to select broodstock with progeny that are more tolerant to changing environmental conditions. If so, managers would either need to (1) limit sea ranching to the areas where such populations occur in order to preserve the existing differences in the genetic structure of sandfish populations[223,224]; or (2) permit releases anywhere to increase production and accept that sandfish resources would become more genetically homogeneous.

Adaptations to reduce the potential impact of ocean acidification on the growth and survival of sandfish will be difficult. If increased mortality due to acidification jeopardises the viability of sea ranching operations, production of sandfish may be limited to ponds, where 'liming' of pond substrate can help maintain pH at desired levels. However, substantial prices would need to be received for bêche-de-mer from pond-reared sandfish to adapt all sandfish production to pond farming systems. Most PICTs do not presently have an infrastructure of ponds and it is debatable whether purpose-built ponds would be profitable.

Vulnerability

The vulnerability of proposed sea ranching projects for sandfish in Fiji and New Caledonia to climate change and ocean acidification is projected to be low under the B1 and A2 emissions scenarios in 2035, and under B1 in 2100. The vulnerability of investments in sandfish farming and sea ranching in more tropical areas is expected to increase to low to moderate under A2 in 2100.

Sea cucumber pen damaged by a cyclone, Fiji

Photo: Cathy Hair

11.3.2.8 Trochus

Exposure and sensitivity

- **Temperature:** The projected changes in SST (Chapters 2 and 3) are not expected to cause any problems for hatchery-reared trochus released in restocking projects – laboratory experiments show that juvenile trochus recover quickly from heat stress when exposed to temperatures as high as 40°C[225].
- **Rainfall:** Trochus are distributed naturally in intertidal and shallow subtidal coral reef habitats[113] and can be expected to have similar salinity preferences as corals. Therefore, the projected increases in runoff from high islands in the tropical Pacific (Chapters 2 and 7) are expected to make some inshore reefs unsuitable for releasing trochus.
- **Ocean acidification:** There is uncertainty about how trochus acquire the calcium carbonate they use to construct their aragonite shells. There is some circumstantial evidence that they obtain some of it by scraping algae from the surface of dead coral with their toothed radula while feeding. This evidence comes from observations that trochus reared in tanks where coral rubble was added to

the substrate developed heavier shells than those in tanks without coral rubble. However, the improvements in shell strength may have been due to the greater abundance of diatoms on the increased surface area provided by the rubble. Even though shell strength can be improved by addition of coral rubble, shells of hatchery-reared trochus are still weaker than those of wild individuals[116], and have a different shape[226] (**Figure 11.14**). As a result of these shell deformations, projects releasing hatchery-reared trochus into the wild are already susceptible to high mortality rates[76,116]. If scraping dead coral surfaces does not help provide calcium for trochus to build their shells, ocean acidification can be expected to increase this mortality further.

- **Sea-level rise:** The projected changes in sea level (Chapter 3) are expected to affect the availability of the structurally complex intertidal and shallow subtidal habitats required by juvenile trochus[227], especially in locations where a greater depth of water makes the existing habitats unsuitable and steep terrain prevents the formation of new intertidal areas.

- **Cyclones:** Powerful waves have caused heavy mortality of transplanted trochus[228]. Therefore, the success of projects releasing trochus can be expected to be susceptible to cyclones. While the more intense cyclones projected to occur in the future are likely to kill many of the trochus on reefs, mortality may be proportional to the size of the shells and the time after release – as trochus grow they move into deeper water where both their size and the depth should increase their resilience to the effects of storms.

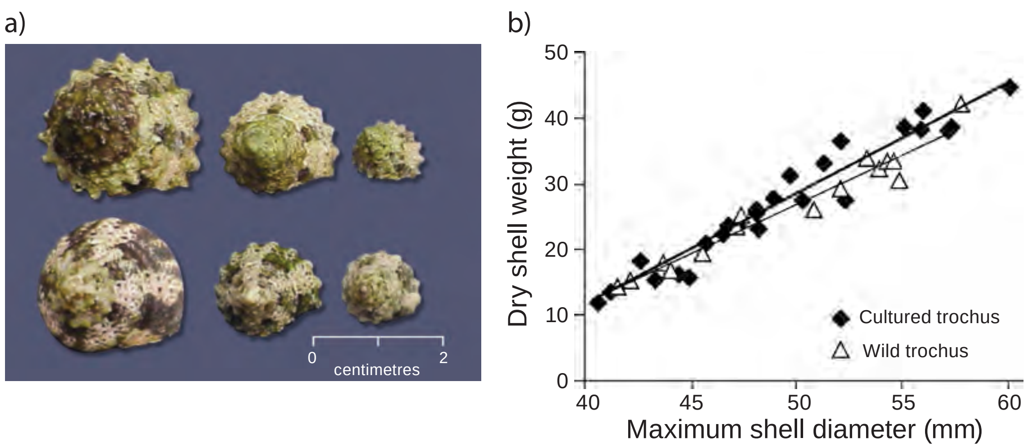


Figure 11.14 (a) Differences in shell shape of wild (upper) and hatchery-reared (lower) juvenile trochus (photo: Steven Purcell), and (b) variation in the relationship between basal shell diameter and shell weight for cultured and wild trochus (source: Clarke et al. 2003)[116].

- **Habitat alteration:** The projected effects of higher water temperatures, increased runoff and ocean acidification on coral reefs and other coastal habitats (Chapter 5) are not expected to have many adverse effects on the habitat for trochus. For example, juveniles often use 'rock pool' habitats with boulders and crevices in the intertidal zone, whereas adults graze algae from the surface of coralline rock and dead massive corals in subtidal areas[113]. Indeed, the degradation of coral reefs may provide more suitable habitat for trochus.

Potential impact and adaptive capacity

The projected changes to the salinity of coastal waters surrounding high islands in the tropics are expected to make some of the reefs previously occupied by trochus unsuitable for this species. On the other hand, degradation of coral reefs may well provide increased areas for colonisation of the algae grazed by trochus. Nevertheless, the projected combined direct and indirect effects of climate change on survival and growth of trochus are expected to have a minor, negative impact on the usefulness of restocking as a management measure for trochus fisheries. The reduced fitness of hatchery-reared animals for survival in the wild due to weakness of their shells remains a major obstacle. If this deficit is exacerbated by ocean acidification following release, the increased rates of predation expected to occur may mean that the benefits of releasing cultured juveniles rarely exceed the costs of producing them. Release of hatchery-reared juveniles is already considered to be less effective than re-distribution of adults as a method for replenishing severely overfished populations of trochus[76] and any additional effects of ocean acidification on released cultured juveniles may remove it as an option altogether.

An adaptation to improve the survival of cultured trochus released in the wild is to reduce the effects of shell deformities resulting from the hatchery process. Juveniles should also be released at sizes > 40 mm in areas that not only provide them with protection from predators but also with access to the coralline substrata they seem to need to construct the strongest shells possible[76,116]. Such areas are expected to increase as a result of the projected degradation of coral reefs (Chapter 5).

Vulnerability

Where the release of cultured juveniles provides the only option for restoring local stocks of trochus, restocking initiatives are expected to have low vulnerability to climate change and ocean acidification under the B1 and A2 emissions scenarios in 2035. Until the uncertainty about how trochus acquire calcium carbonate to construct their shells, and the possible effects of ocean acidification on this process, are resolved, vulnerability is also estimated to remain low in 2100 under both emissions scenarios.

11.3.3 Climate change, aquaculture and aquatic diseases

Plans to increase production of the commodities listed above through farming systems, or the release of cultured juveniles into the wild, are already exposed to an additional risk – the threat of disease. Disease is a greater consideration for aquaculture than for the capture fisheries described in Chapters 8, 9 and 10 because diseases can proliferate when aquatic animals and plants are reared in close proximity[229]. Some of the main diseases which threaten aquaculture in the tropical Pacific and worldwide are listed in **Table 11.4**. Climate change may increase the risk posed by disease through alterations in the distribution, prevalence and virulence of pathogens (bacteria, viruses, fungi and parasites), and changes in the susceptibility of the host species used to produce the commodities[230].

Ideally, the projected changes to disease risk should be added to the list of indirect threats which aquaculture is likely to be exposed to in the tropical Pacific as a result of climate change. However, this is not yet possible because the likely responses of existing diseases in the tropical Pacific, and those with the potential to spread here, are not well understood. Instead, we outline the main factors expected to cause changes in the distribution, prevalence and virulence of aquaculture diseases in the region to raise awareness of this potentially severe problem.

Table 11.4 Examples of common diseases of aquaculture commodities worldwide, and in the tropical Pacific.

Disease	Commodity
Epizootic ulcerative syndrome (EUS)[254]	Freshwater fish
Viral nervous necrosis (VNN)[255]	Marine fish
Koi herpes virus (KHV)[256]	Koi and common carp
White spot syndrome virus (WSSV)[237]	Shrimp (Penaeidae)
Taura syndrome virus (TSV)[237]	Shrimp *Litopenaeus vannamei*
Infectious hypodermal and hematopoietic necrosis virus (IHHNV)[237]	Shrimp *Litopenaeus vannamei, L. stylirostris*
White tail disease (WTD)[257]	Freshwater prawn *Macrobrachium rosenbergii*
Syndrome 93 vibriosis[65]	Shrimp *Litopenaeus stylirostris*
Syndrome 85[258]	Pearl oyster *Pinctada margaritifera* (French Polynesia)
Bacterial infection *Vibrio harveyi*[259]	Pearl oyster *Pinctada margaritifera* (Cook Islands)

11.3.3.1 Factors likely to increase the risk of diseases in the future

Globalisation

The increasing volume of international trade in live aquatic animals and their products has created new mechanisms for transboundary spread of pathogens. As a result, there is more potential for both known and unknown disease problems to arise quickly in any country's aquaculture sector, often with serious economic, social and ecological consequences[231]. Such diseases are often difficult or impossible to eliminate once established. The continued expansion of global trade can be expected to exacerbate these problems and the onus is on PICTs to improve biosecurity in line with international protocols[232,233]. All countries have a responsibility to guard against the intensification of aquaculture in a way that promotes the transfer of diseases. The concern is that unless aquaculture operations are well designed and managed, they can provide a platform for the emergence of serious pathogens[234], with consequences for neighbours and trading partners.

Environmental change

A delicate balance exists between the host, the pathogen and the environment; disturbing this balance can create opportunities for pathogens to proliferate. In particular, temperature fluctuations, salinity changes, low pH, low dissolved oxygen, habitat alterations and harmful algal blooms can stress the host and suppress its immune system[235]. Stress disturbs the normal functions of the host and promotes a series of 'stress responses' designed to restore homeostasis, which are not always effective. For example, an animal may increase production of stress hormones (corticosteroids) to help mobilise additional energy, but these stress hormones suppress the immune system, rendering the host more susceptible to disease. As a result, the incidence of disease outbreaks and rates of disease transmission often increase during changes to the environment. The host also becomes more susceptible to opportunistic infections. Particularly severe problems can occur when the environmental change not only stresses the host, but also favours the pathogen[117].

Many environmentally-induced disease problems are caused by obligate pathogens, which are an integral part of the ecosystem and normally exist in a biological cycle that involves association with one or more hosts. New diseases usually emerge as a consequence of a major shift in the environment of the pathogen due to anthropogenic influences – increases in temperature due to climate change are of particular concern in this regard.

The sequence of disease development also depends to a large extent on environmental factors. Virulence of the pathogen, disease resistance mechanisms of the host and the prevailing environmental factors determine the pathology in the host and the outcome of the disease development process[235]. Environmental perturbations can modulate this process significantly and lead to increased disease outbreaks and spread of diseases to new geographical areas.

11.3.3.2 Possible effects of climate change and ocean acidification on diseases

Climate change and ocean acidification have the potential to alter the host-disease relationships outlined above. In a recent survey, the World Animal Health Organisation found that 71 of its 126 member-states were 'extremely concerned' about the expected impact of climate change on animal disease. In fact, 58% of the members had already identified at least one disease associated with climate change that was new to their territory or had returned to their territory recently[236].

Warming of the climate and ocean acidification can be expected to alter the incidence of diseases of aquatic organisms directly by affecting the pathogens themselves, and indirectly by altering the biology of the hosts[238]. The modes of transmission and virulence of pathogens can also be influenced by climate change[239]. Under a changing climate, PICTs are likely to witness alterations in development and survival rates of pathogens, transmission of diseases and susceptibility of hosts.

11.4 Integrated vulnerability of the aquaculture sector

When the direct effects of the projected changes to water temperature, rainfall, ocean acidification, sea-level rise, cyclone intensity, and the expected indirect effects of alterations to habitats, are integrated it is evident that:

1. existing and planned aquaculture activities to produce tilapia, carp and milkfish in freshwater ponds for food security are likely to benefit from the anticipated changes to surface climate; and
2. aquaculture enterprises producing commodities for livelihoods in coastal waters are likely to encounter production problems due to changes projected to occur in the tropical Pacific Ocean (**Table 11.5**).

Aquaculture operations for tilapia, carp and milkfish are expected to benefit strongly from projected increases in temperature and rainfall, and to cope with other changes to the environment even though some are negative (**Table 11.5**). These projected benefits are expected to be apparent by 2035, and well established by 2100, especially under the A2 emissions scenario, when surface temperatures are expected to be 2.5–3.0°C higher, and rainfall 10–20% greater, in tropical areas relative to 1980–1999 (Chapter 2). A proviso is that the changing climate does not limit access to the ingredients needed to formulate appropriate diets for tilapia, carp and milkfish, particularly fishmeal.

The expected boost to freshwater pond aquaculture as a result of climate change by 2035 should also apply to freshwater prawns. However, this trend may be reversed by 2100 due mainly to the temperature sensitivity of freshwater prawns and the effects of higher temperatures on stratification of ponds.

Although some commodities for livelihoods are likely to benefit from the projected changes in specific environmental variables, when the effects of all variables are integrated most commodities dependent on coastal waters for hatchery production and/or grow-out are expected to incur production losses, albeit at a low vulnerability rating (**Table 11.5**). The exceptions are shrimp farming and seaweed culture. For shrimp farming in 2035, the expected benefits from the projected increases in water temperatures may well improve yields. For seaweed farming, the expected increases in SST and rainfall by 2035 are likely to mean that the industry has a moderate rather than low vulnerability to crop losses due to increased incidence of outbreaks of epiphytic filamentous algae and tissue necrosis.

By 2100, the effects of climate change and ocean acidification on all livelihood commodities are expected to be negative and their vulnerability increases (**Table 11.5**). Under the A2 emissions scenario, seaweed farming and production of marine ornamentals are likely to have a high vulnerability, and the culture of pearls a moderate vulnerability. Shrimp farming, marine fish farming and sea ranching/pond farming of sea cucumbers are expected to have a low to moderate vulnerability, while the vulnerability of trochus is rated as low until further research elucidates the mechanisms by which they acquire calcium carbonate to construct their shells.

Vulnerability does not necessarily imply that there will be overall reductions in productivity of these commodities in the future. Rather, it indicates that the efficiency of enterprises producing the commodity will be affected. Total production could still increase if the operations remain viable, albeit with reduced profit margins, and more enterprises are launched. For example, seaweed production targets that have been set for the next decade of 1000–2000 tonnes per year (engaging several hundred households) in both Fiji and Solomon Islands should still be achievable, but not necessarily in the same places or with the methods now in use.

11.5 Opportunities

11.5.1 New commodities

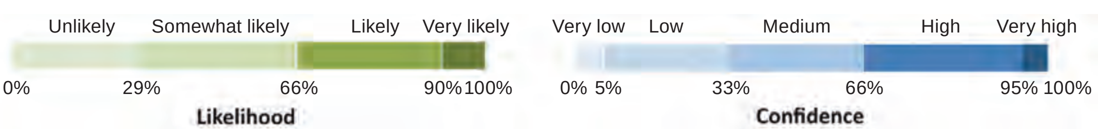
Pacific Island countries and territories are likely to have limited opportunities to produce new aquaculture commodities as a result of climate change, and other major drivers influencing the sector[240]. The development of markets for biodiesels as a renewable source of energy to replace fossil fuels is perhaps a possibility[241]. Marine algae have many advantages over land-based crops for producing biodiesel, including fast growth rates, high yields and no requirement for freshwater resources. Governments and enterprises around the world are now investing in research and development to reduce the operating and capital costs involved in large-scale culture of marine microalgae required to make production of biodiesel commercially viable.

Several PICTs, particularly those with atolls that have consistently high water temperatures and sunshine hours, and access to fertilisers (e.g. phosphate), may be in a position to convert part of their lagoons into the pond infrastructure needed to culture marine algae for biodiesel. Such operations are likely to be less affected by the projected increases in temperature because appropriate strains of microalgae can be selected or developed to suit the conditions.

Table 11.5 Projected direct effects of various features of climate change, and indirect effects due to habitat alteration, on the productivity of the main aquaculture commodities in Pacific Island countries and territories. Also shown is the overall vulnerability of these commodities, based on the integration of these effects, under the B1 and A2 emissions scenarios in 2035 and 2100. Note that specific and integrated effects can be negative (-) or positive (+). Likelihood and confidence estimates have been provided for each assessment.

Commodity	Specific effects						Vulnerability		
	Temp.	Rain-fall	Ocean acid.	Sea-level rise	Cyclones	Habitat alteration	B1/A2 2035	B1 2100	A2 2100
Food security									
Tilapia and carp	(+)	(+)	n/a	(-)	(-)	n/a	L (+)	L (+)	L (+)
Milkfish	(+)	(+)	(-)	(+/-)	(-)	(-)	L (+)	L (+)	L (+)
Livelihoods									
Pearls	(-)	(-)	(-)	(+/-)	(-)	n/a	L (-)	L (-)	M (-)
Seaweed	(-)	(-)	(+)	(+)	(-)	n/a	M (-)	M-H(-)	H (-)
Shrimp	(+/-)	(-)	nil	(-)	(-)	n/a	L (+)	L (-)	L–M (-)
Marine ornamentals	(-)	(-)	(-)	(-)	(-)	(-)	L (-)	M (-)	H (-)
Freshwater prawn	(+)	(+/-)	n/a	(-)	(-)	(+)	L (+)	L (-)	L (-)
Marine fish	(-)	(-)	(-)	(-)	(-)	(+/-)	L (-)	L (-)	L-M (-)
Sea cucumbers	(+/-)	(-)	(-)	(-)	(-)	(-)	L (-)	L (-)	L-M (-)
Trochus	nil	(-)	?	(-)	(-)	(+)	L (-)	L (-)	L (-)

Temp. = Temperature; Ocean acid. = ocean acidification; L = low; M = moderate; H = high; nil = no projected effect; ? = undetermined; n/a = non applicable.



Care will be needed in evaluating (1) the potential for rainfall to reduce salinities of ponds below acceptable limits in tropical areas; and (2) the effects of large-scale ponds on lagoon environments, noting that modification to such atolls to increase productivity have been suggested in the past[242]. Comprehensive assessments of the opportunity cost of these farming operations, for example loss of fishing areas and other social services normally provided by lagoons, will also be required.

New Caledonia plans to develop biosaline agriculture of halophytes like *Sarcocornia quinqueflora* on available salt pans as a source of food for people, and as a replacement for fishmeal in shrimp feeds. This initiative may also provide a potential source of biomass for biodiesel.

11.5.2 Harnessing new opportunities to expand production

Making the most of the potential benefits of the changing climate to increase production of freshwater commodities for food security will not only mean adapting production techniques, it will involve positioning producers to take advantage of local market opportunities. For example, enterprises growing tilapia in peri-urban areas will need incentives and strategies to market their product, so that they can help fill the expected shortfall in the supply of coastal fisheries for growing urban populations caused by progressive degradation of coral reefs (Chapters 5, 9 and 12).

Other opportunities to expand the production of existing aquaculture commodities are likely to emerge for small-holders, and also at the industry level. For example, small-holders could diversify ways of growing-out wild juvenile freshwater prawns *M. lar*, which are likely to be more abundant in the future (Section 11.3.3.5), by combining culture of these prawns with taro as freshwater habitats expand under the projected higher levels of rainfall (Chapter 7). The potential to diversify industrial shrimp farming to produce *P. monodon*, and perhaps other species, as coastal waters warm is described in Section 11.3.3.3.

11.5.3 Market instruments and climate change

Adaptations to make the most of the opportunities expected to be provided by climate change will need to go beyond the tasks of investing in production of promising new commodities, and expanding production of commodities favoured by the changing environmental conditions and local market place. Effective adaptations will also need to respond to international market forces, and related issues and actions arising from global concerns about climate change. Increased understanding of climate change in many of the larger developed countries importing aquaculture products is creating new marketing challenges. Below, we highlight some of the key factors that will need to be considered when developing plans to maintain and expand the benefits of aquaculture for PICTs in the face of climate change.

11.5.3.1 Carbon labelling

There is increasing interest in Europe and the USA in 'labelling' products with information on the amount of carbon dioxide released during manufacturing processes, and transport to markets, to indicate the 'carbon footprint' associated with the item[iv]. Products from aquaculture are unlikely to be exempt from this scrutiny – increasingly consumers can be expected to seek information on carbon to reduce the footprint of their purchases.

Of particular interest are the direct use of fossil fuels for production and transport, and the indirect use of fossil fuels associated with conversion of natural ecosystems (which may influence natural greenhouse gas sinks and reservoirs), construction, services, stock respiration and waste decomposition[243]. Intensive and semi-intensive farming systems have the highest energy consumption[244]. Small-scale, extensive systems producing seaweed and molluscs have the lowest energy consumption and carbon footprints, and may be net absorbers of CO_2.

The challenge for aquaculture enterprises will be to adapt, either through regulation or voluntary approaches, to meet the demands of the market. However, there will be limited scope to reduce carbon emissions associated with the long distances that commodities such as shrimp need to be shipped to international markets. This is likely to affect the competitiveness of products from PICTs. The concern over 'food miles' to date has not, however, taken into account the social and economic benefits of trade for poorer countries and communities[245]. Careful monitoring and attention to all dimensions of carbon labelling are needed to negotiate such market barriers, even for small producers[243]. Novel schemes of energy conservation and carbon offset through improved efficiency along the supply chain, marketing strategies, and better management of natural resources are required to develop new business models for the sector[246].

The issues described above are likely to compound the existing problems of low competitiveness due to distance from markets, and the relatively high labour costs and low economies of scale compared with Asian producers, already faced by aquaculture enterprises in the tropical Pacific. Although the implications of carbon labelling are expected to take some time to have an impact on the market place, because of the processes involved in standardising carbon auditing and applying labelling schemes equitably[247], PICTs should act now to integrate the effects of a changing global market place in their strategies to expand aquaculture.

11.5.3.2 Green labelling

The benefits of producing aquaculture products in an environmentally sensitive and sustainable way are already apparent to PICTs and various schemes have been promoted, e.g. certification by the Marine Aquarium Council[248,249], in the hope that

iv Carbon Trust (www.rpm-solutions.ca/CSR/CarbonFootprint_methodology_full.pdf) conforming producers will receive more market share and/or premium prices. There is some doubt, however, about how certified production methods will influence the willingness of consumers to pay higher prices. For example, the higher rates of survival of captive-reared aquarium specimens compared with those taken from the wild appears to be an equally strong, if not stronger, factor influencing the purchases of some marine ornamental fish by hobbyists[48]. Nevertheless, innovative farming systems supplying products from well-maintained healthy ecosystems might be expected to attract higher prices in the future, especially if they also reduce carbon footprints. Where products must still be transported long distances, other features of the production system that are environmentally friendly may also attract consumers. Organically-produced tilapia and milkfish products, which have potential markets in Australia, New Zealand and United States of America, are in this category.

11.5.4 Financing options for future development

The aquaculture sector in PICTs could be assisted by the emerging opportunities for international financing to assist developing countries adapt to climate change (Chapter 13). There is also the possibility that some of the habitats that help underpin coastal aquaculture could be maintained by carbon offset schemes. Such opportunities may emerge because seafood is traded internationally in large volumes and has a significant carbon footprint compared with many other products from primary industry. Recent FAO/WorldFish estimates show that 3.7 teragrams (Tg) of CO_2 are released from air freight of seafood each year and 300–340 Tg of CO_2 from sea and land freight[250]. The offset of these CO_2 emissions may have substantial value in carbon trading markets. Estimates of actual values are now needed, together with an understanding of supply chain dynamics, efficiencies and opportunities for improvements. Seafood traders and larger buyers can then evaluate the potential for future reduction in carbon footprints through purchase of offsets in carbon sinks in coastal habitats, such as mangrove planting (if eligible).

Other schemes to remove carbon from the atmosphere, or prevent release of carbon, that become eligible under the international carbon trading system should also be evaluated to determine whether they provide opportunities to support aquaculture activities, and the ecosystems on which they depend.

11.6 Uncertainty, gaps in knowledge and future research

11.6.1 Commodities for food security

Given the potential importance of freshwater pond aquaculture in helping to provide the animal protein needed in the diets of inland communities in PNG, Solomon Islands and Fiji[4] (Chapters 1 and 12), there is a need to reduce the uncertainty about surface temperature and rainfall patterns at spatial scales relevant to this activity. In particular, information from the most recent set of global climate models needs to be downscaled to the level of river catchments, so that planners, managers and stakeholders can make the best possible assessments of projected conditions for efficient farming of tilapia, carp and milkfish.

Such research will not only enable PICTs to capitalise on the expected opportunities to increase production of freshwater fish commodities for food security (Section 11.3.1), it will also indicate which areas within countries and territories may not be suitable for this form of aquaculture.

Tilapia farming, Vanuatu

Photo: Paul Christian Ryan

Although downscaled information on surface climate and rainfall will identify the locations where pond aquaculture will be technically feasible in the future, PICTs also need reliable information to assess any potential impacts of fish introduced for farming on freshwater biodiversity. Such information will enable PICTs to weigh up the advantages and disadvantages of promoting pond aquaculture as a way of supplying animal protein to inland communities[5]. The design of research to provide this information will need to ensure that any effects of escaped fish on freshwater biodiversity are not confounded with changes to freshwater habitats caused by poor management of vegetation in catchments (Chapter 7). It will also be important to identify whether Nile tilapia has any effects on freshwater biodiversity over and above any impact attributed to *O. mossambicus*. This may be unlikely because the Mozambique tilapia *Oreochromis mossambicus* has long been established throughout many of the freshwater habitats in the region, and is potentially more invasive than the Nile tilapia *O. niloticus* because of its broader salinity tolerances[118].

11.6.2 Commodities for livelihoods

Downscaled projections for SST and rainfall will also be needed to plan how best to manage shrimp farming in the future. A key research question for the shrimp industry in New Caledonia, and of interest to other commodities, is how variability in temperature is likely to alter with global warming. In particular, downscaling to determine whether temperature fluctuations during the short 'spring' and 'autumn' seasons, which presently create stresses that lead to chronic shrimp mortality (Section 11.3.2.2) (**Figure 11.6**), are likely to be reduced over time or get worse. This information will be instrumental in decision-making about investment to develop the industry further.

Downscaled projections for SST and rainfall should also help identify the locations and timeframes where farming of the seaweed *Kappaphycus alvarezii* is likely to remain viable. These projections should help determine whether seaweed farming can be expanded to Vanuatu as temperatures warm. If so, gender-based, socio-economic research will be needed to find out if the relatively low incomes available from growing seaweed are likely to (1) meet the expectations of coastal communities; and (2) enable sufficient and regular production over the long term to facilitate establishment of enterprises to export the products.

Much uncertainty also surrounds the potential effects of ocean acidification on the aquaculture commodities produced in coastal waters to support livelihoods. Although there is medium to high confidence in the assessments that the survival and growth of pearl oysters, corals and giant clams are likely to be adversely affected by ocean acidification, it remains to be seen whether micro-sites can be located where the aragonite saturation levels stay within acceptable limits due to the buffering effects of nearby reefs and macrophytes. Locating such sites is also likely to be needed to maintain the quality of pearls. Given the great significance of pearl farming in the region, the experiments on the effects of ocean acidification on pearl quality are a priority. Possible effects of ocean acidification on the production of shrimp should also be investigated, although they are not expected to be particularly detrimental.

Experiments on the effects of ocean acidification are needed to determine if this process changes (1) the behaviour of postlarval milkfish and their recruitment success; and (2) the size and strength of spicules in sandfish. It would also be interesting to know whether the feeding behaviour of trochus confers some resistance to the projected decline in aragonite saturation levels.

11.6.3 Other important considerations

As outlined in Section 11.3.4, there are many reasons to be concerned that the abundance and virulence of the viruses, bacteria, fungi and parasites that routinely cause production losses in aquaculture may alter with the changing climate. Research should focus on determining the possible responses of known pathogens to global warming in the high-value pearl and shrimp industries, and identifying scenarios and developing mitigation strategies to manage any projected consequences.

A key gap in information across the region is the lack of accurate statistics needed to track and forecast the development of the sector. A uniform system is needed for collecting data on the quantities or volumes of commodities produced for commercial sale or subsistence, number of farm units, number and gender-balance of people employed part and full time, and export value. This system should be based on standardised methods, and is essential not only for planning development of the sector, but also for monitoring the effectiveness of adaptations to assist producers to capitalise on the opportunities presented by climate change, and to minimise the adverse effects. The system for data collection on production from aquaculture and sea ranching should also be designed in line with international protocols to provide the information required by FAO[251]. Strategies for collecting these data need to be assessed carefully. Where it is not practical to organise regular dedicated surveys, censuses and household income and expenditure surveys can be used to gather basic information[252].

The fledgling nature of many aquaculture commodities in the tropical Pacific means that the research required to reduce uncertainty should not be limited to investigating the effects of changes in environmental variables on production. In many cases, the primary need is to make the basic production methods more efficient and reliable. The knowledge available for optimising the survival of hatchery-reared sandfish released in the wild is a case in point. Although estimates of survival have been made for four sites in New Caledonia[103], reliable information is needed for other PICTs where governments wish to investigate the possible benefits of sea ranching sandfish. Allied to this is the need to produce better maps of the extent and quality of seagrass beds (Chapter 6), to assess the locations of suitable release habitats.

11.7 Management implications and recommendations

The onus is on the managers and stakeholders of aquaculture sectors across the region to adapt future activities to optimise the benefits and minimise the losses expected to occur under the changing climate – some commodities are expected to be easi er to produce, and others more difficult. The aim should not be just to maintain the present level of activities, but to pave the way for the sector to continue to grow. The challenge is to re-align investment to harness the full potential of the more promising commodities, while assisting disadvantaged producers to adapt, either by changing their methods or diversifying into those commodities favoured by the changing climate. Failure to do so has a large opportunity cost.

In making judgements about where and how to invest in future development, priority should not be given only to potentially lucrative export commodities. Promoting and supporting the commodities for food security, and assisting small-holders to maintain viable operations for seaweed and marine ornamentals for as long as possible, will have great social benefits. Both activities aid marginalised communities with few other opportunities to earn income.

Collecting farmed *Kappaphycus* seaweed, Solomon Islands

Photo: Gideon Tiroba

In addition to forming alliances with regional technical agencies to undertake the activities described in Section 11.6 to reduce uncertainty and fill gaps in knowledge, there are a number of actions that PICTs can make to fulfil these goals. These actions are outlined below.

- Promote the benefits of freshwater aquaculture as a vehicle for supplying fish to growing human populations in (1) rural areas where it is not practical to provide better access to tuna and other large pelagic fish (Chapter 9), and (2) peri-urban areas where low-value tuna and bycatch are not landed by industrial fleets (Chapter 8). Until the research on the possible effects of Nile tilapia on freshwater biodiversity is complete, applying this method to help provide food security for rural communities and the urban poor should be limited to catchments where Mozambique tilapia is well established. Similar recommendations apply for carp farming in PNG. There is no need to promote pond aquaculture of tilapia in PICTs where supplies of coastal fish are expected to meet recommended consumption levels well into the future (Chapter 12).

- Support the development of pond aquaculture by (1) seeking expert advice and resources to design and construct the types of hatchery systems and networks that will allow fingerlings with fast growth characteristics to be distributed effectively, even to remote areas; (2) formulating cost-effective feeds for semi-intensive and intensive farming systems based on locally available ingredients wherever possible; and (3) increasing the knowledge and capacity of fisheries staff and extension officers for providing training in all forms of freshwater pond aquaculture, and post-harvest methods.
- Ensure that any ponds constructed for freshwater aquaculture near rivers, or in lowland areas, are situated where they will not be affected by the higher floods expected to eventuate as a result of projected changes to rainfall.
- Anticipate saltwater intrusion into freshwater ponds used to grow tilapia or *Macrobrachium* spp. located close to the coast and make provision to convert such ponds for milkfish farming or salt-tolerant tilapia where these fish already occur in the catchment and are well accepted as food fish.
- Identify micro-sites (close to existing coral reefs and seagrass meadows) where aragonite saturation levels are likely to remain high enough for good growth and survival of pearl oysters, and formation of high-quality nacre.
- Identify which existing shrimp ponds can be modified by elevating the walls and floor to continue to function under rising sea levels, and which ones will need to be abandoned in favour of new ponds further landward at higher elevations. Assess which alternative commodities could be produced in ponds that are no longer suitable for shrimp in ways that do not impede landward migration of mangroves and seagrasses.
- Reduce exposure of all commodities dependent on fishmeal (tilapia, carp, milkfish, shrimp, freshwater prawns, marine fish) to shortages in global supplies due to climate change and worldwide demand by (1) ensuring that processing plants for tuna in the region use the waste products to produce fishmeal with a high-protein content in efficient ways; (2) lobbying for priority access to local supplies of fishmeal; (3) using undesirable introduced freshwater fish species (e.g. walking catfish *Clarias batrachus*, climbing perch *Anabas testudineus*) in PNG to produce fishmeal; (4) progressively replacing fishmeal with alternative sources of protein; and (5) promoting Best Management Practice (BMP) for feeding farmed fish to increase feed efficiency.
- Fast track the completion of research needed to develop micro-particle feeds for shrimp to reduce dependence on *Artemia*.
- Map the location of all aquaculture activities and supporting infrastructure to identify any risks to operations posed by expected changes in environmental variables, increased storm surge, sea-level rise or pathogens. Valuable lessons can be learned here from the mapping of pearl oyster farms in Manihiki Atoll, Cook Islands[253].

- Assess designs of equipment and infrastructure for aquaculture and improve the resistance of these components to the effects of stronger cyclones.
- Strengthen national capacity and regional networks to adopt and implement aquatic biosecurity measures, including capacity for monitoring, detecting and reporting aquatic animal diseases, using international protocols[237], to prevent introduction of new pathogens. This will require cross-sectoral approaches involving fisheries, quarantine and environmental agencies[13].
- Maintain a watching brief on advances in aquaculture technologies in other regions to identify opportunities to diversify the sector in ways with potential to perform well under the changing climate. Consider transfer of such technologies, with the necessary biosecurity precautions, to increase the resilience of the sector.

A shrimp farm, New Caledonia Photo: Yves Harache

- Ensure that any application of 'carbon labelling' initiatives for regional seafood products is treated equitably, and takes into account the special vulnerabilities of the economies of small and remote PICTs within the global market place. This may require assistance from regional trade organisations.
- Analyse the carbon footprints of aquaculture systems in the region, and investigate better ways to conserve energy, and market products, through improved efficiency along the supply chain, innovative strategies, and better management of natural resources. Use regional trade and preferential access agreements to facilitate this process.
- Promote mangrove replanting and wetland conservation programmes in suitable habitats (Chapter 6) to capture carbon and enhance the coastal habitats on which some aquaculture based on collection of wild-caught juveniles ultimately depends.

- Strengthen national capacity to manage the environmental issues related to development of aquaculture, such as application of Environmental Impact Assessment procedures that consider both present and future risks associated with specific proposals.

Development of independent capacity in these areas will be beyond the capability of some PICTs. For those countries and territories with an aquaculture sector, or the potential to develop one, it will be important to identify the alliances and partnerships that can help provide the necessary support. Collaboration with regional technical agencies will be a key strategy for effective implementation of the recommendations listed above.

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