Explaining Ocean Warming:

Causes, scale, effects and consequences

Edited by D. Laffoley and J. M. Baxter

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Cover photos: Clockwise from top: King penguins (*Aptenodytes patagonicus*) on Middle Beach (Brothers Point in distance), Macquarie Island, Southern Ocean. (© Robbie Kilpatrick/Australian Antarctic Division, November 2015, Image RS31770,Image Antarctica); a colony of black coral with small crabs moving amongst the branches (image courtesy of Department of BIS, UK); seagrass (*Zostera marina*) © SNH/Ben James; Hurricane Catarina on March 26th, 2004, off SE Brazil. Image courtesy of NASA.

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4.5 Impacts and effects of ocean warming on the contributions of fisheries and aquaculture to food security

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Summary

- Fisheries and aquaculture play a vital but often poorly acknowledged role in global food security. Together, fisheries and aquaculture provide 4.3 billion people with ~15% of their average per capita intake of animal protein. By 2050, an additional 75 million tonnes of fish will be needed to help feed more than 9 billion people.
- The recent revolution in aquaculture, and continued improvements to management of capture fisheries, have potential to provide the additional fish required. However, warming of the world's ocean could disrupt these important initiatives.
- Ocean warming will result in 'winners' and 'losers. Changes in distributions of fish stocks as species seek their optimal temperatures, and as the habitats on which they depend are altered by higher water temperatures, will result in decreases in fisheries production in some countries and increases in others. Similarly, the prime locations for mariculture are expected to be altered by ocean warming, resulting in changes in yield patterns among countries.
- The effects of ocean warming on the contributions of marine fisheries and mariculture to food security should not be considered in isolation from those of other drivers. Rapid population growth, fish exports and poor fisheries management also affect availability of fish in many developing countries. These drivers often create a gap between how much fish is needed for good nutrition and local fish harvests. The main effects of ocean warming are to alter (increase or decrease) the gap.
- Changes to the gap due to ocean warming are expected to be greatest in tropical and subtropical countries. Adaptations are needed to minimize, and to fill, the gap.
- Adaptations to minimize the gap include reducing the impact of local stressors on fish habitats through improved integrated coastal management and marine spatial planning; keeping production of fisheries within sustainable bounds using the most appropriate management measures for the national context and a climate-informed ecosystem approach; and improving supply chains.
- The most important adaptation for filling the gap will be the expansion of environmentally sustainable mariculture (and freshwater aquaculture). However, for some developing countries, the most practical adaptations for filling the gap will be re-allocating some of the catch of large and small pelagic fish taken by industrial fleets to small-scale fishers, and/or arranging for industrial fleets to land more of their catch in local ports.

Ocean warming effect	Consequences
Total production of fish from capture fisheries has levelled off at about 90 million tonnes per year	Aquaculture now supplies the remainder of the ~130 million tonnes of fish used directly for food
An additional 75 million tonnes of fish will be needed to help feed more than nine billion people by 2050	Continued improvements to fisheries management will be needed but expanded aquaculture production will be required to meet most of the demand
Ocean warming is expected to increase progressively due to continued greenhouse gas emissions	The plans to optimize production from marine fisheries and to expand mariculture are likely to be affected by ocean warming
Distributions of fish stocks will change as fish species seek their optimal ocean temperatures	Marine fisheries production will increase in some countries and decrease in others
Prime locations for mariculture will change as the ocean warms	Countries will become more or less suitable for mariculture and patterns of yields among countries will change
Rapid population growth, fish exports and poor fisheries management are reducing availability of fish per capita in many developing countries	A gap is emerging between how much fish is needed for good nutrition and how much fish is available locally
Ocean warming will widen this gap in some countries and reduce it in others	Practical adaptations are needed to minimize, and to fill, the gap

4.5.1 Introduction

Fisheries and aquaculture play a vital but often poorly acknowledged role in global food and nutrition security (Béné *et al.,* 2015, 2016). The ~130 million tonnes of fish[1] currently produced from marine and freshwater capture fisheries and aquaculture used directly for human consumption (Figure 4.5.1) provide 4.3 billion people with about 15% of their average per capita intake of animal protein (HLPE, 2014). Furthermore, about 10% of the world's population – predominantly from developing and emergent countries – rely heavily on fisheries and aquaculture for the income needed to buy food (Allison *et al.,* 2013; HLPE, 2014).

In recent decades, total production from capture fisheries has levelled off at about 90 million tonnes per year, with about 75% used directly for food (Figure 4.5.1), because most marine resources are now fully exploited, and in some cases over-exploited (FAO, 2014a). Rapid development of aquaculture has met the remainder of the demand (FAO, 2014a). In fact, the rate at which aquaculture has increased has enabled global fish supply to outpace population growth, and the supply of other sources of animal protein (De Silva, 2012a; FAO, 2014a; Youn *et al.,* 2014). Although capture fisheries will always need to be an important source of fish, particularly in developing countries (Hall *et al.,* 2013), most of the expected future demand for fish will have to come from aquaculture (Merino *et al.,* 2012; FAO, 2014a). Rice and Garcia (2011) provide a potent example of estimated future demand – they calculate that an additional 75 million tonnes of fish will be required to provide more than 9 billion people with 20% of their dietary protein requirements by 2050.

There is optimism that continued improvements in aquaculture related to feed formulation, feeding technologies, farm management and selective breeding can supply the future needs for fish (FAO, 2014a). A particularly beneficial development is the reduced dependence on fish meal for feeds, which decouples marine fisheries and aquaculture production, paving the way for more wild fish to be used directly for human consumption. There is also the prospect that total sustainable production from capture fisheries could increase by up to ~20% with improved management (OECD-FAO, 2013; Costello *et al.,* 2016). Similarly, there is a view that fish production from inland capture fisheries is under-estimated (Beard *et al.,* 2011; Bartley *et al.,* 2015) and that there is scope for freshwater fish resources to make significant additions to supplies of food fish (Youn *et al.,* 2014), particularly among rural communities in developing countries. On the other hand, failure to address the many factors that affect the production of capture fisheries, including habitat

1 Fish is used here in the broad sense and includes finfish, shellfish (invertebrates), sharks and rays

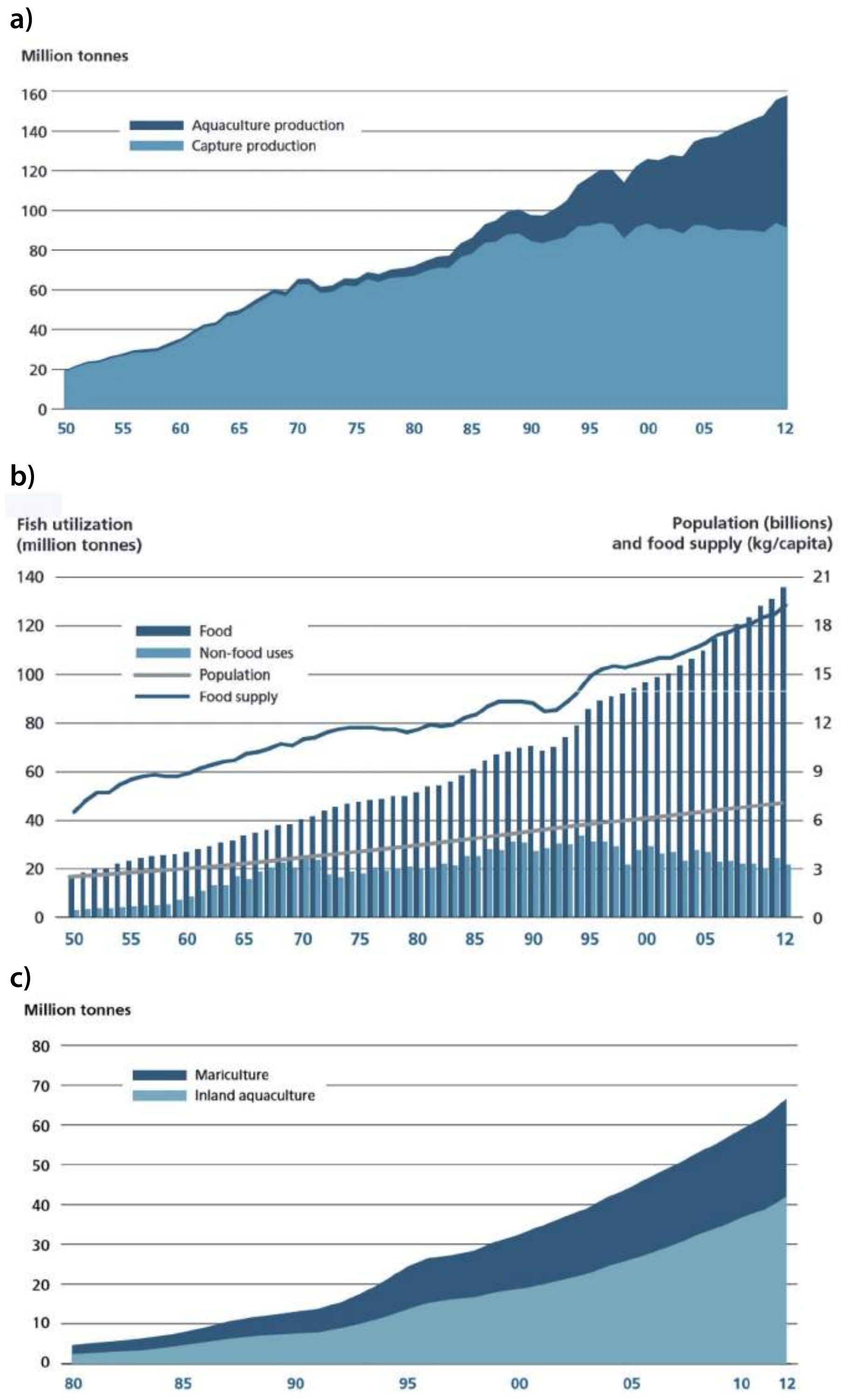

Figure 4.5.1 a) World capture fisheries and aquaculture production, 1950–2012; b) world fish utilization and supply, 1950–2012; and c) global inland aquaculture and mariculture production, 1980–2012 (source: FAO, 2014a).

degradation, over-capacity and a range of socio-economic drivers (Gillett and Cartwright, 2010; Hall, 2011), could reduce present-day harvests from the wild and widen the gap to be filled by aquaculture.

Climate change poses an additional risk to the initiatives underway to supply more than 200 million tonnes of fish for human consumption by 2050. The best laid plans for better management of capture fisheries and technical improvements in aquaculture could be affected by changes to the environment beyond the control of managers. One of the main consequences of increased greenhouse gas (GHG) emissions – warming of the world's ocean – has the potential to disrupt these plans. Because 87% of capture fisheries production (FAO, 2014a), and 47% of aquaculture production (FAO, 2016), comes from marine and coastal (hereafter marine) waters, any such disruptions are expected to have a significant effect on global seafood production. The potential effects may be even more significant because there are limits to the expansion of inland aquaculture (which currently accounts for 90% of finfish aquaculture production) due to foreshadowed restrictions on availability of fresh water (FAO, 2014a). This means that a greater percentage of the additional 75 million tonnes of fish needed by 2050 will have to come from marine aquaculture (hereafter 'mariculture').

Here, we review assessments of the projected effects of ocean warming on the contribution of marine fisheries and mariculture to food security and livelihoods. We focus mainly on developing country regions because they have the greatest dependency on fish for nutrition (Bell *et al.,* 2009; Davies *et al.,* 2009 ; Kawarazuka and Béné, 2011; Wanyonyi *et al.,* 2011; Lam *et al.,* 2012; Barnes-Mauthe *et al.,* 2013; FAO, 2014a; Portner *et al.,* 2014). This is not to say that the effects of ocean warming are insignificant for fisheries in developed countries. They are significant, as demonstrated by several studies from the North Atlantic and North Pacific (e.g. Cheung *et al*., 2012; Hollowed *et al*., 2013; Colburn *et al*., 2016; Hare *et al*., 2016), and by our summary of global assessments of the effects of ocean warming on marine fisheries (para 4.5.5). Alterations in fish catch from developed countries, such as Japan and those in the EU and North America, due to ocean warming can also be expected to have impacts on food security in the developing country regions by influencing exports to developed countries.

We begin with a brief summary of the expected effects of ocean warming on marine fish species and ecosystems, report the projected effects of such changes on the production of marine fisheries and mariculture, and conclude with the implications and practical adaptations to minimize the risks and capitalize on the opportunities.

Our analysis is limited to ocean warming and does not consider the effects of ocean acidification on production from marine fisheries and mariculture; such effects are discussed by Hilmi *et al.* (2015) and have been shown to vary with taxa and region. The effects of global warming on inland aquaculture in general have been assessed by De Silva and Soto (2009) and De Silva (2012b); specific cases have also been considered by Phan *et al.* (2009), Nguyen *et al.* (2014, 2015) and Li *et al.* (2016), for example.

We found winners and losers. Projected changes in the distribution and abundance of species, primary productivity supporting marine fisheries, and environmental conditions suitable for mariculture and proliferation of parasites, pests and diseases, indicate that fish production is likely to increase in some countries/regions and decrease in others (Harvell *et al.,* 1999; Allison *et al.,* 2009; Barange *et al.,* 2014; FAO, 2014a; Hoegh-Guldberg *et al.,* 2014).

4.5.2 Effects of ocean warming on marine species and ecosystems

Although some fish species can respond to the warming of the ocean described in Sections 3.11 and 3.12 by adjusting *in situ* (Maggini *et al.,* 2011), the most widely documented impacts of climate change on species supporting marine fisheries are shifts in distributions to areas of preferred temperature (Last *et al.,* 2011; Pinsky *et al.,* 2013; Jung *et al.,* 2014). Such range shifts are due largely to the direct effects of changes in temperature on the physiology and behaviour of species (Pörtner, 2001; Pörtner and Farrell, 2008; Pratchett *et al.,* 2010; Section 3.11) (Figure 4.5.2). In particular, changes in temperature can have significant effects on the timing of reproduction and development duration (phenology) and, therefore, dispersal of eggs or larvae. Temperature changes also affect individuals and populations through altered rates of metabolism, consumption and assimilation (Buckley, 2013). In addition, changes in ocean temperature affect the size and hence productivity of species (Cheung *et al.,* 2013a), which may require changes in management (Audzijonyte *et al.,* 2013, 2014, 2016).

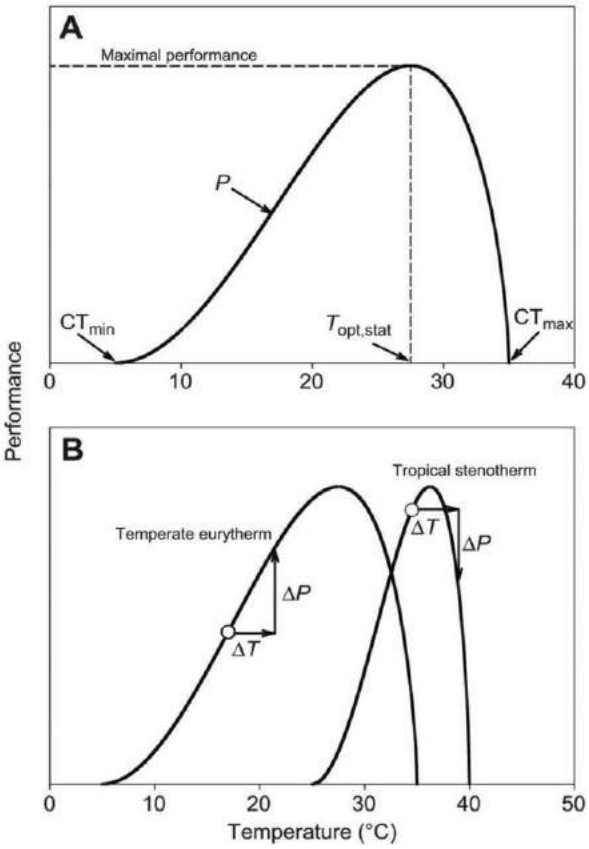

Figure 4.5.2 (A) Thermal performance curves typically have a characteristic, unimodal shape exemplified by performance as a function of body temperature. Often the reaction norm's peak is shifted to the right of centre, such that performance increases relatively slowly up to T_{opt}, but decreases rapidly above T_{opt}. Although performance curves are generally modelled as functions, performance is typically only measured at a small number (4–8) of discrete temperatures in empirical studies. (B) A given increase in temperature (ΔT) results in an increase in nominal performance (ΔP) for a temperate fish and shellfish species, but the same temperature increase results in a decrease in nominal performance for a tropical species capable of living or surviving within a narrow temperature range (source: Dowd *et al.,* 2015).

In general, marine species are 'tracking' ocean warming by moving towards the poles, resulting in range extensions at poleward boundaries of their distributions (analogous to species invasions) and range contractions at equatorward boundaries (analogous to local species extinctions) (Chen *et al.,* 2011; Poloczanska *et al.,* 2013; Bates *et al.,* 2014; Section 3.11). These changes in distribution are evident in waters surrounding all continents, and for a wide range of marine organisms, e.g. phytoplankton (Thompson *et al.,* 2009, 2015; Section 3.2), seaweeds (Wernberg *et al.,* 2011; Nicastro *et al.,* 2013; Section 3.3), invertebrates (Pitt *et al.,* 2010; Chen *et al.,* 2011) and fish (Cheung 2008, 2010; Last *et al.,* 2011; Sunday *et al.,* 2015; Sections 3.11 and 3.12).

Ocean warming can also have indirect effects on fisheries production by altering primary productivity (Le Borgne *et al.,* 2011; Blanchard *et al.,* 2012; Barange *et al.,* 2014) and the benthic habitats that support fisheries (Hoegh-Guldberg *et al.,* 2011; Waycott *et al.,* 2011). Ocean warming can increase stratification of the water column (Ganachaud *et al.,* 2011; Hoegh-Guldberg *et al.,* 2014), reducing upwelling and the availability of nutrients required for the growth of phytoplankton at the base of the food webs supporting fisheries (Le Borgne *et al.,* 2011). The contributions of some benthic habitats to fisheries production are particularly vulnerable to ocean warming. In particular, the corals that provide habitat for fish and invertebrates in many tropical developing countries are being adversely affected by bleaching due to elevated sea surface temperature (SST) (Pratchett *et al.,* 2008; Hoegh-Guldberg *et al.,* 2011, 2014; Ainsworth *et al.,* 2016; Section 3.8).

Changes in distribution, phenology and abundance of marine species related to the direct and indirect effects of ocean warming can have significant impacts on the structure and function of ecosystems (Tylinakias *et al.,* 2008, Johnson *et al.,* 2011; Marzloff *et al.,* 2016). Where shifts in the distributions or abundances of species occur at different times and rates (Sunday *et al.,* 2012, 2015; Pecl *et al.,* 2014), links between species can be broken allowing, for example, some species to escape from predators and exploit a wider range of environments (Jaeschke *et al.,* 2012; Section 3.11).

4.5.3 Effects on fish supply

Changes in the production of marine fisheries and mariculture due to the direct and indirect effects of ocean warming need to be considered together with other factors affecting the supply of fish (Gillett and Cartwright, 2010; Bell *et al.,* 2011a; Hall *et al*., 2011). In many developing countries, rapid population growth is driving a gap between sustainable fish harvests and the amount of fish needed to contribute to good nutrition (see para. 4.5.3.1). The effects of ocean warming have the potential to widen or reduce this gap. In other developing countries, trade policies that result in the majority of fish being exported limit local supplies of fish and overshadow the expected effects of ocean warming on availability of fish per capita (Delgado *et al*., 2003; Béné and Heck, 2005; Hobday *et al.,* 2015). Fisheries management approaches can also have a profound effect on fish supply and the effects of poor management are likely to exceed the effects of ocean warming for many years to come.

Below, we summarize the importance of fish to food security and livelihoods, and the expected effects of projected ocean warming on marine fisheries, in five developing country regions. Several of these projections rely on model forecasts, which remain susceptible to some uncertainty and bias (Cheung *et al*., 2016b). Therefore, a measure of caution is needed in applying percentage projected changes to fish catch derived from these models. We also summarize the expected effects of ocean warming on mariculture worldwide and the key findings from several global assessments of the effects on marine fisheries.

4.5.3.1 Pacific Islands

Traditionally, Pacific Island coastal communities have had some of the highest rates of fish consumption in the world (3-4 times the global average) and relied on fish to provide 50-90% of their dietary animal protein (Bell *et al.,* 2009). Much of this fish has come from subsistence coastal fisheries based on coral reefs (Dalzell *et al.,* 1996; Pratchett *et al.,* 2011). Rapid population growth in several Pacific Island countries is expected to alter this situation. By 2035, population growth alone will reduce the availability of fish per capita below the 35 kg of fish per person per year recommended for good nutrition of Pacific Island people (SPC, 2008; Bell *et al*., 2009). The direct effects of increased SST on fish metabolism projected to occur under a high GHG emissions scenario, and the indirect effects of ocean warming on the quality of coral reef fish habitats as a result of increased coral bleaching and ocean acidification, are expected to reduce production by ~20% by 2050 and exacerbate this situation (Bell *et al.,* 2011b, 2013; Pratchett *et al.,* 2011).

Table 4.5.1 Estimates of coastal fisheries production based on coral reef area for selected Pacific Island countries, the amount of fish needed for food in 2020 and 2035, and expected surplus (+) or deficit (-) in fish supply, relative to the recommended 35 kg per person per year or traditionally higher levels of fish consumption, for each country for each period. The quantities of tuna needed to fill the gap in fish supply and the percentage of average national tuna catch required to provide this tuna in 2020 and 2035 is also shown (after Bell *et al.,* 2015a).

Country	Coastal fish production (tonnes.y^{-1})[a]	Fish needed for food (tonnes)[b]		Surplus (+)/ deficit (-) coastal fish (tonnes)[c]		Tuna needed for food (tonnes)		Average tuna catch (tonnes)[d]	Percentage of average tuna catch required[e]	
		2020	2035	2020	2035	2020	2035		2020	2035
PNG[f]	98,760[g]	117,000	169,100	-18,200	-73,800	18,200	63,200[h]	597,657	3.0	10.6
Solomon Is[i]	27,610[j]	25,400	35,600	2,210	-7,990	0	7,990	144,454	0	5.5
Kiribati[k,l]	12,960	10,900	13,400	2,060	-890	4,900	6,370	330,177	1.5	1.9
Nauru[k]	130m	700	800	-570	-670	570	670	99,033	0.6	0.7

a Based on median estimates of sustainable fish harvests of 3 tonnes per km^2 (Newton *et al.,* 2007)
b Based on estimates in supplementary material for Bell *et al.* (2015a)
c Calculations for 2035 include a 2-5% reduction in the production of coastal fisheries due to the effects of climate change (Pratchett *et al.,* 2011)
d Based on the 5-year average total tuna catch (all gear types) for the period 2009-2013, rounded to the nearest tonne.
e Assumes that all tuna will come from industrial fishing within the EEZ and does not allow for catches from nearshore FADs, the contribution of bycatch, or the effects of climate change on tuna catch (Bell *et al.,* 2013)
f Fish needed for food based on providing different quantities per capita for the urban, coastal/riverine and inland populations of PNG (see Bell *et al.,* 2015a)
g Includes 17,500 tonnes of freshwater fish.
h Allows for freshwater pond aquaculture to supply 1 kg of fish per person per year by 2035 (Bell *et al.,* 2011b), reducing the overall deficit in fish of 73,800 tonnes to 63,200 tonnes
i Fish needed for food based on recommended fish consumption of 35 kg per person per year (see Bell *et al.,* 2015a)
j Includes 2000 tonnes of freshwater fish
k Fish needed for food based on recent, traditional levels of fish consumption for rural and/or urban populations (Bell *et al.,* 2009)
l National average incidence of ciguatera fish poisoning, renders several species of coral reef fish unfit for human consumption at some locations
m Based on reconstructions of catches of coastal fish by the 'Sea around us' project, University of British Columbia

The rich tuna resources of the region provide a potential solution. Allocation of a relatively small percentage of the tuna catch from the exclusive economic zones of Pacific Island countries would provide the additional fish required (Bell *et al.,* 2015a) (Table 4.5.1). However, the effects of ocean warming under a high GHG emissions scenario will make this solution easier to apply in some countries than in others. Preliminary modelling of the effects of the most abundant tuna species in the region, skipjack tuna *Katsuwonas pelamis* (Figure 4.5.3), indicates that there is likely to be an eastward shift in the relative abundance of this important fish species (Bell *et al.,* 2013; Lehodey *et al.,* 2013) (Figure 4.5.4). Over time, it should be easier for coastal communities in Kiribati, Cook Islands and French Polynesia in the central and eastern Western and Central Pacific Ocean (WCPO) to catch tuna than it is for coastal communities in the western WCPO, e.g. in Papua New Guinea (PNG) and Federated States of Micronesia. However, there will still be large (albeit reduced) quantities of tuna available in the western WCPO in the future for both export and domestic food security (Figure 4.5.4).

Figure 4.5.3 Women selling skipjack tuna caught by small-scale fishers around Tarawa Atoll, Kiribati. © Johann Bell.

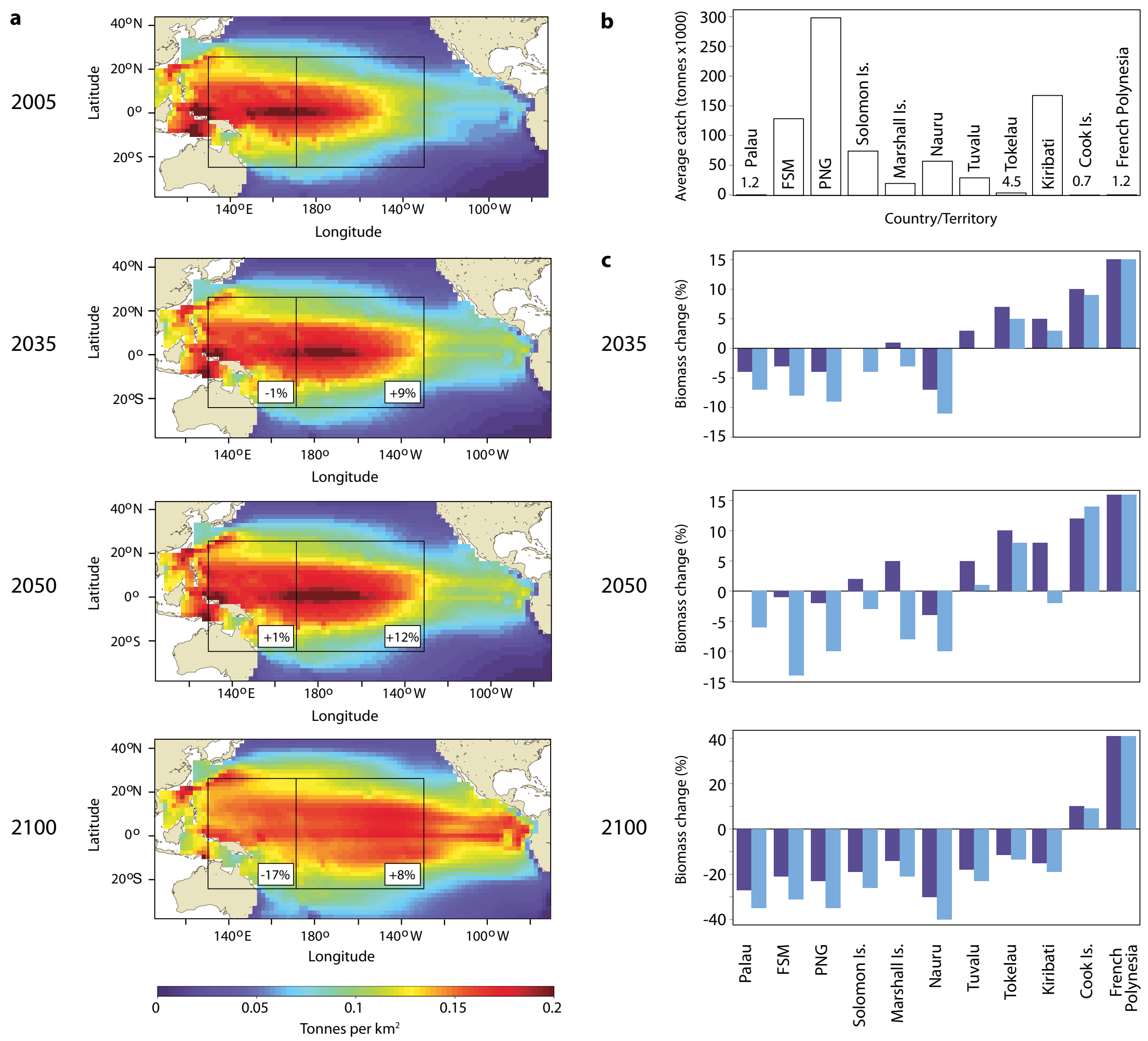

Figure 4.5.4 Projected distributions of skipjack tuna biomass across the tropical Pacific Ocean under the IPCC SRES A2 emissions scenario. (a) Simulations for 2005, 2035, 2050 and 2100 derived from the SEAPODYM model (Lehodey *et al.*, 2013), including projected average percentage changes for the boxed areas east and west of 170ºE. (b) Recent average annual catches of skipjack tuna (2000–2010) from exclusive economic zones of selected Pacific Island countries and territories; FSM = Federated States of Micronesia, PNG = Papua New Guinea. (c) Estimated changes in biomass relative to virgin stock levels (dark blue), and incorporating fishing effort 1.5 times greater than the average for 1990–1999 (light blue), for 2035, 2050 and 2100 (source: Bell *et al.*, 2013).

4.5.3.2 South-east Asia

Based on the ‘Sea Around Us[2]’ catch data (Pauly and Zeller, 2016), total marine fisheries catch in South-east Asia increased from around 2.5 million tonnes per year in the 1950s to more than 25 million tonnes in the 1990s. Catches have since stabilized at around that level, with a decreasing trend in the last decade.

The increase in marine and freshwater fish catch, and in the production from freshwater aquaculture and mariculture, has enabled per capita fish consumption in South-east Asia to increase from ~13 to 32 kg per person per year since 1961 (FAO, 2012). As a result, present-day fish consumption in the region is well in excess of the global average of ~19 kg per person per year (FAO, 2014a). Nevertheless, many fish stocks in the region have been over-exploited, with resource abundance at the end of the 20th Century being 5-30% relative to the level in the 1950s (Silvestre *et al.*, 2003). Correspondingly, marine fisheries in the South China Sea area are now characterized by high numbers of fishing vessels and collectively employ millions of people (Table 4.5.2).

2 www.seaaroundus.org

Table 4.5.2 Summary of approximate number of fishing vessels and the number of people employed in marine and coastal fisheries (from 2000–2012, depending on data availability), together with estimated landed value in 2012, in selected countries/areas in the South China Sea (SCS) (source: Dyck and Sumaila, 2010; ; Sumaila and Cheung, 2015)

Country/Area	No. fishing vessels	No. people employed	Landed value (USD x 1000)
China - northern SCS	92,300	648,800	9,807,035
Hong Kong	4,000	8,800	296,774
Indonesia	76,800	320,000	1,084,985
Malaysia - east coast, Sabah, Sarawak	24,600	56,000	1,219,133
Philippines –regions NCR, CAR, I, III, IV	117,000	627,000	817,335
Taiwan	231,600	271,600	2,731,292
Thailand	58,100	168,700	1,286,627
Vietnam	129,500	540,000	4,384,180

Maintaining the significant contribution of marine fisheries and mariculture to per capita fish consumption and livelihoods in South-east Asia will be a formidable challenge as the ocean continues to warm. It will depend greatly on future GHG emissions and the level of effective fisheries management (Sumaila and Cheung, 2015). Under a high 'business as usual' emissions scenario (RCP8.5), harvests from marine fisheries in South-east Asia are projected to decrease by 10% to >30% by 2050 relative to 1970-2000, depending on the country (Figure 4.5.5) (Cheung *et al.,* 2016a). The reduced harvests are expected to be driven by local extinctions as species change their distributions in response to the increases in water temperature. Overall, loss of more than 20% of the original fish species richness in South-east Asia is projected by 2050 (Jones and Cheung, 2015).

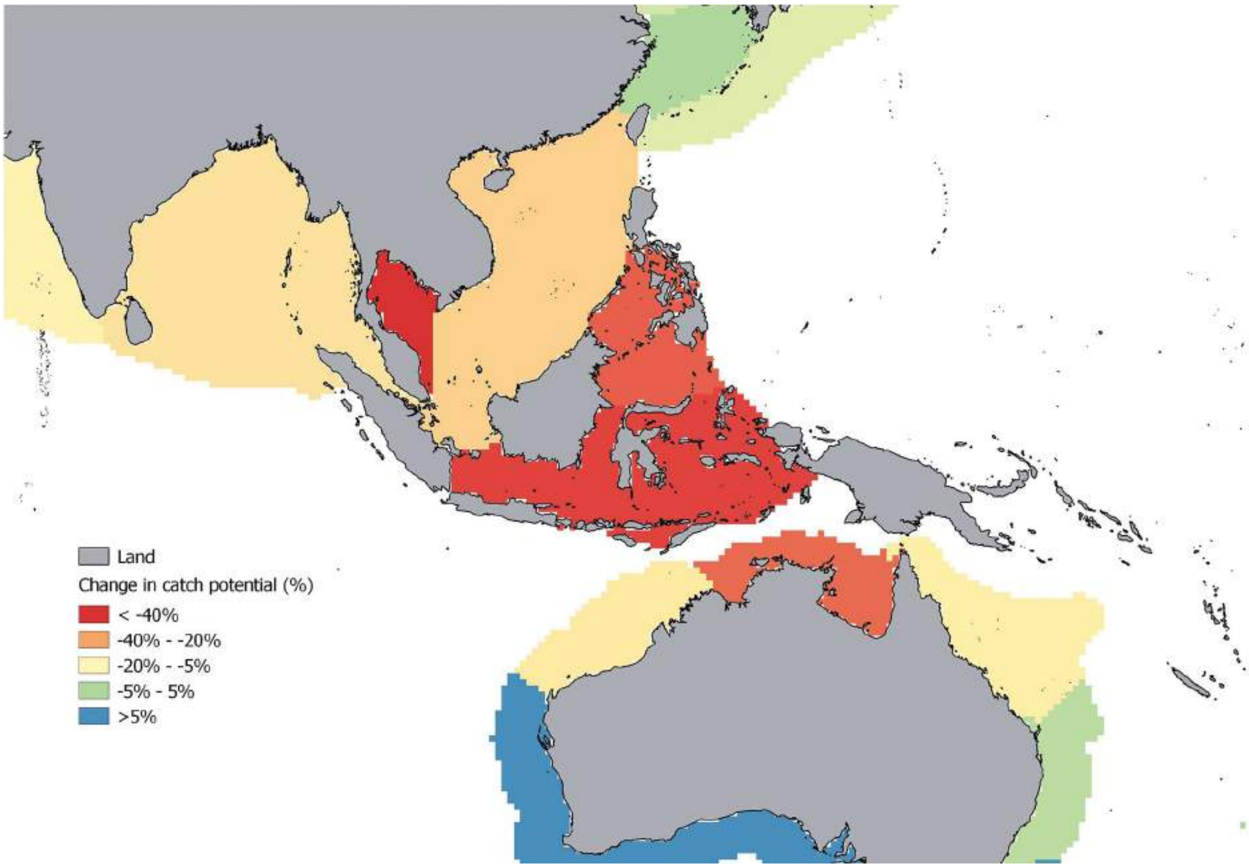

Figure 4.5.5 Multi-model ensemble projections of mean percentage changes in potential fish catch from South-east Asia by 2050, relative to recent catch levels (1971–2000), under the RCP 8.5 emissions scenario (source: Cheung *et al.,* 2016a).

Under-performing fisheries management in the region will exacerbate the impact of climate change. For example, a recent assessment of the effects of a business as usual emissions scenario combined with status quo levels of fisheries exploitation in the South China Sea, using trophodynamic models, projected that the biomass of several groups of fish species (including groupers, sharks, threadfin breams and croakers) could decrease by 50% or more (Sumaila and Cheung, 2015). On the other hand, a low GHG emissions scenario can reduce the impacts from climate change and ocean acidification on the marine ecosystem. Simultaneously, substantial reduction of fishing will rebuild over-exploited fish stocks. Both of these measures would be expected to have a positive impact on the biomass of most stocks. However, reducing effort would result in lower catches for several of the main species while stocks are rebuilt, creating an even wider gap in fish supply to be filled by mariculture (and freshwater aquaculture) (see Para. 4.5.4).

4.5.3.3 East Africa and Western Indian Ocean

The high population density in coastal and small island developing states in East Africa and the Western Indian Ocean (WIO) relative to coral reef area (Table 4.5.3), coupled with poverty-driven dependence on fishing for food and cash, has caused degradation of these important fish habitats through over-harvesting and destructive fishing (Wells *et al.,* 2007; Wafar *et al.,* 2011; Samoilys *et al.,* 2015). As a result, fisheries based on coral reefs now only make a modest contribution to per capita fish consumption, typically less than 5 kg per year, for communities living within 25 km of the coast (Table 4.5.3). Seychelles and Mayotte are the exceptions. By 2030, coral reefs will provide even less fish per person due to predicted population growth. Ocean warming, which has caused widespread coral mortality (Obura, 2005; Ateweberhan *et al.,* 2011) and reduced productivity of coral reef fisheries (Graham *et al.,* 2007) in the WIO, is exacerbating the situation. Consequently, small-scale fishers in the region are being encouraged to transfer more of their effort offshore to tuna and other oceanic fish species. Because tuna and other oceanic species fall within the mandate of the Indian Ocean Tuna Commission, increased access to some of these fish stocks, e.g. yellowfin tuna, by small-scale fishers

Table 4.5.3 Estimated availability of coral reef fish per capita (kg) in 2015 and 2030 for coastal populations in countries from East African and the Western Indian Ocean.

Country	Coral reef area (km²)[a]	Estimated reef fish production (tonnes yr⁻¹)[b]	Total human population in 2015[c]	2015		2030	
				Population within 25 km of coast[d]	Reef fish per capita (within 25 km of coast) (kg/person/yr)	Population within 25 km of coast[e]	Reef fish per capita (within 25 km of coast) (kg/person/yr)
Somalia	710	4,260	10,787,000	3,290,035	1.29	5,030,365	0.85
Kenya	1724	10,344	46,050,000	2,809,050	3.68	3,990,132	2.59
Tanzania	3580	21,480*	53,470,000	7,271,920	2.95	11,278,072	1.90
Mozambique	1860	11,160	27,978,000	9,148,806	1.22	13,549,245	0.82
Madagascar	2230	13,380	24,235,000	5,622,520	2.38	8,342,720	1.60
Seychelles	1690	10,140	96,000	96,000	105.63	101,000	100.40
Comoros	430	2,580	788,000	788,000	3.27	1,081,000	2.39
Mayotte (France)	985	5,910	240,000	240,000	24.63	344,000	17.18
La Reunion (France)	18.6	112	861,000	861,000	0.13	947,000	0.12
Mauritius	870	5,220	1,273,000	1,273,000	4.10	1,310,000	3.98

* Likely to be an over-estimate because large areas of Tanzania's reefs have been destroyed by dynamite fishing (Wells, 2009; Slade and Kalangahe, 2015); a = sources: UNEP (2009) except Kenya (Samoilys *et al.,* in press), Reunion (Nicet *et al.,* 2015); Mayotte (Andréfouë *et al.,* 2009); b = calculated as total coral reef area in km x 6 tonnes (based on 6.09 tonnes km^{-2} yr^{-1} for Kenya in 2006 (Samoilys *et al.,* in press); c = UN World Population Prospects: 2015 Revision Vol. 1; d = source: UNEP (2009); e = UN World Population Prospects: 2015 Revision Vol. 1.

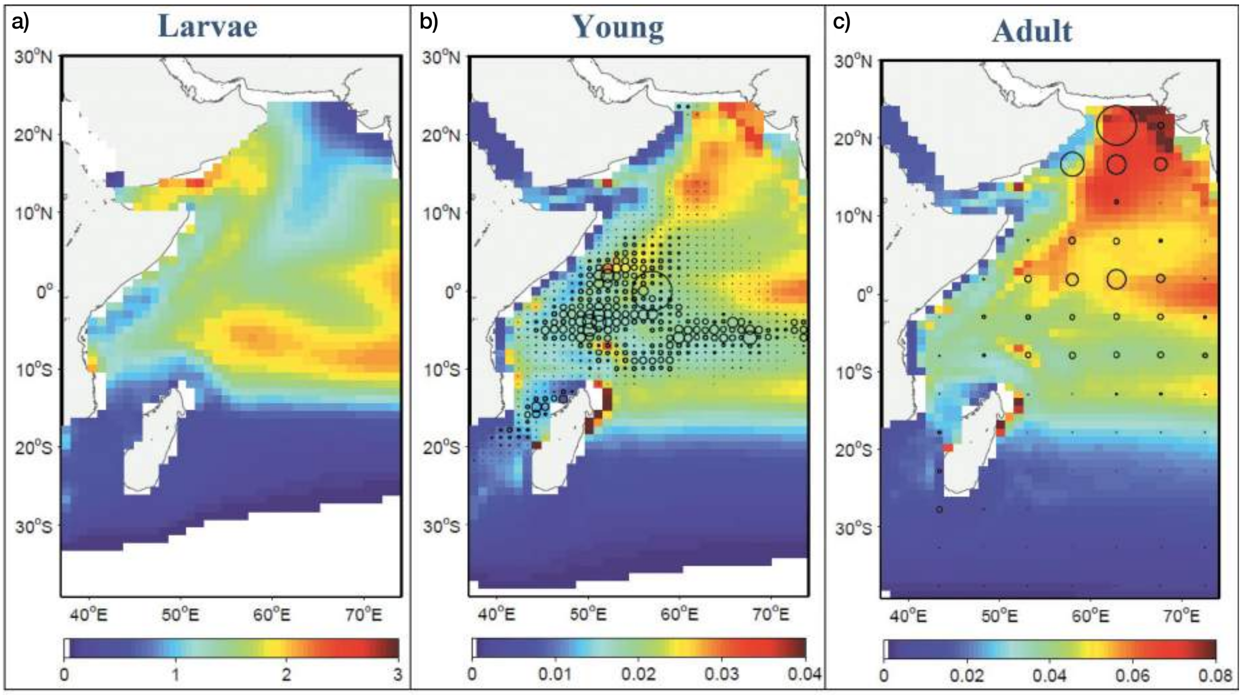

Figure 4.5.6 Reconstruction of the history of yellowfin tuna dynamics and fisheries in the Western Indian Ocean using the SEAPODYM model and results presented in Senina *et al.* (2015). The panels show the average spatial distribution of yellowfin tuna density for three different life history stages: a) larvae, b)young fish caught by purse seine, and c) adults caught by longline. The locations of catches of young fish made by purse seine are shown with circles on panel b) (largest circle radius corresponds to a catch of 200 tonnes) and the locations of catches of adults by longline are shown with circles on panel c) (largest circle radius corresponds to a catch of 10 tonnes).

will need to be accommodated through reallocation of a proportion of the catch of industrial fleets so that no net increase in catch occurs. However, some oceanic fish species in the WIO, such as skipjack tuna and kawakawa tuna, are not currently overfished and not subject to overfishing (IOTC, 2015).

Ocean warming is likely to affect this recommended adaptation to some extent. For example, preliminary modelling of the effects of higher water temperatures on yellowfin tuna, one of the large pelagic fish species commonly caught by small-scale fishers in the WIO (Herrera and Pierre, 2010; Kaplan *et al.,* 2014), indicates that substantial changes in the distribution and abundance of this species are likely to occur in the future (Senina *et al.,* 2015). Relatively good confidence can be placed in these projections because the SEAPODYM model (Lehodey *et al.,* 2008) used for the simulations predicts the historical catch of yellowfin tuna in the main fishing grounds well (Figure 4.5.7).

The modelling indicates that stronger stratification will occur in the upper water column, leading to reduced production of phytoplankton, zooplankton and micronekton in the food web that supports yellowfin tuna in tropical regions of the WIO. The simulations show that distribution of larval yellowfin tuna is likely to become less dense in the equatorial region and increase in the western Arabian Sea by the middle of the century. These changes are driven by a favourable increase in water temperature in the western Arabian Sea and an unfavourable and strong decrease in phytoplankton (primary production) in the equatorial region. By 2050, the density of adult yellowfin tuna is projected to decrease throughout the WIO, with the greatest decreases occurring from Kenya southward (Figure 4.5.6). Simulations at a higher resolution are now needed to confirm the results from the preliminary modelling.

4.5.3.4 West Africa

Although annual per capita fish consumption in most countries in West Africa is lower than the global average (Table 4.5.4), several nations in the region have a relatively high dependence on fish and fisheries for food and income due to the scarcity of other sources of animal protein (Brashares *et al.,* 2004; Smith *et al.,* 2010). Fish is also an important source of the essential micronutrients and vitamins missing from local staples (rice, maize and cassava), in particular, iron, iodine, zinc, calcium and vitamins A and B (Roos *et al.,* 2007; Kawarazuka, 2010; Golden *et al.*, 2016).

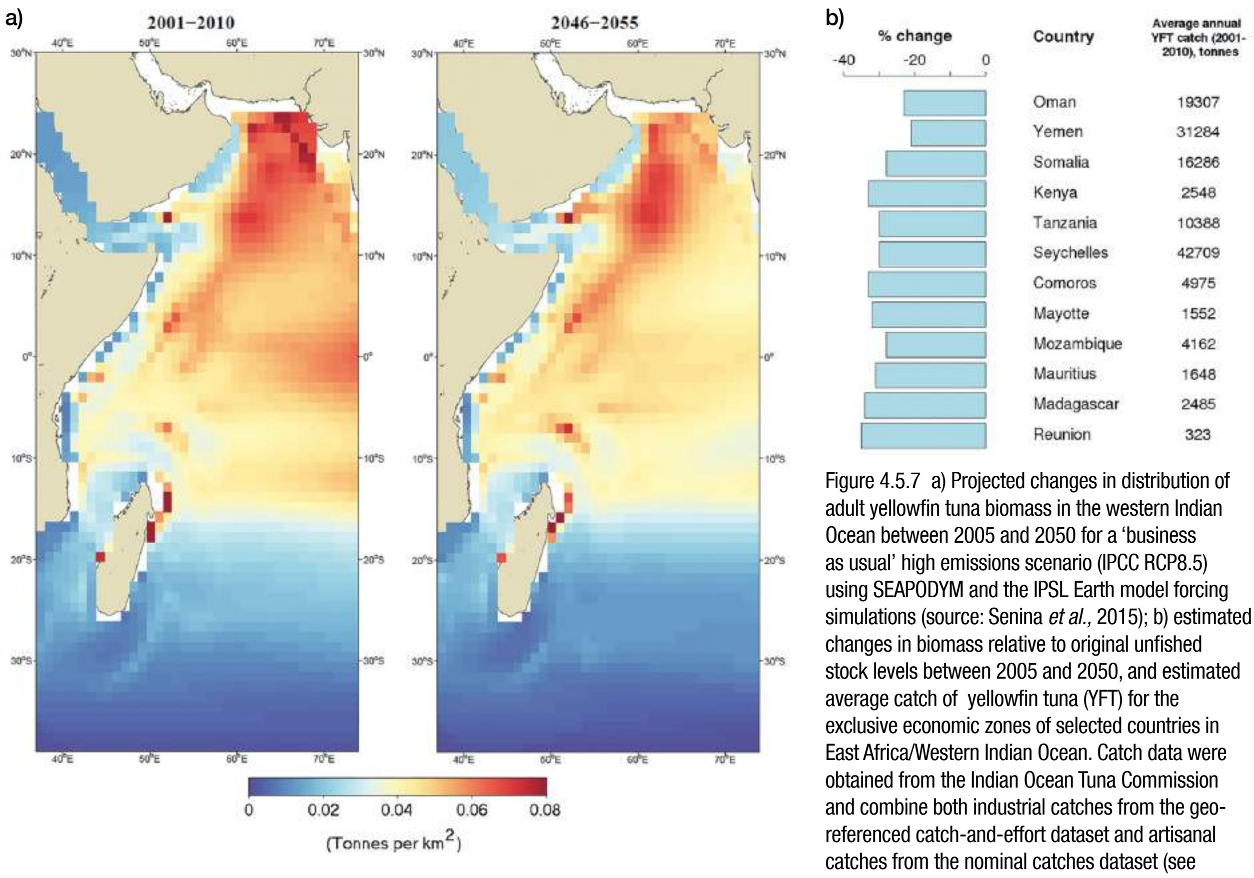

Figure 4.5.7 a) Projected changes in distribution of adult yellowfin tuna biomass in the western Indian Ocean between 2005 and 2050 for a 'business as usual' high emissions scenario (IPCC RCP8.5) using SEAPODYM and the IPSL Earth model forcing simulations (source: Senina *et al.,* 2015); b) estimated changes in biomass relative to original unfished stock levels between 2005 and 2050, and estimated average catch of yellowfin tuna (YFT) for the exclusive economic zones of selected countries in East Africa/Western Indian Ocean. Catch data were obtained from the Indian Ocean Tuna Commission and combine both industrial catches from the geo-referenced catch-and-effort dataset and artisanal catches from the nominal catches dataset (see http://iotc.org/documents/all-ce-files and http://iotc.org/documents/nominal-catch-species-and-gear-vessel-flag-reporting-country, respectively, for an explanation of possible errors involved in combining these datasets).

Table 4.5.4 Estimated annual average per capita food fish supply in West African countries (2007–2011), together with the average volume of fish taken by distant water fishing nations (DWFNs) licensed to fish in a nation's exclusive economic zone, and volume of fish exported, per year.

Country	Fish supply (kg/capita/year)[a]	Fish caught by DWFNs (tonnes)[b]	Fish exports (tonnes)[c]
Sierra Leone	33.2	34, 900	5,600
Gambia	28.9	63,900	3,300
Ghana	26.5	1,700	22,400
Senegal	25.2	281,000	108,200
Côte d'Ivoire	17.5	91,500	40,600
Nigeria	16.0	17,000	22,700
Cape Verde	11.1	3,300	14,500
Guinea	9.4	555,300	7,600
Mauritania	9.2	1,640,200	149,700
Togo	6.8	33,000	1,500
Benin	3.6	3,500	600
Liberia	3.2	71,400	100
Guinea Bissau	1.8	198,600	4,400

[a] based on fish food supply data (source: FAO, 2015)
[b] annual average catch between 2006 and 2010 extracted from the Sea Around Us catch reconstruction database (www.seaaroundus.org)
[c] source: FAO (2016) (http://www.fao.org/fishery/statistics/global-commodities-production/query/en)

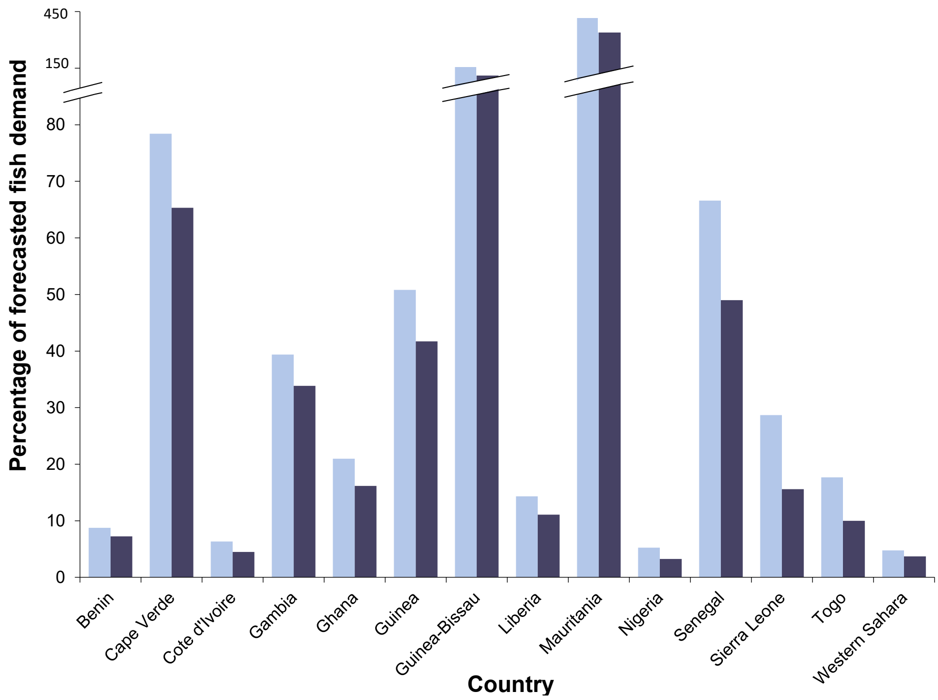

Figure 4.5.8 Percentage of forecasted fish demand expected to be supplied by catches from the wild in West African countries by the 2050s under a high emissions scenario (SRES A1B) (dark blue) and assuming that emissions can be reduced to the year 2000 level (light blue). Future fish demand was estimated using current per capita fish consumption and projected national population growth (United Nations, 2009).

Some countries in the region gain government revenue from licensing distant water fishing nations (DWFNs) targeting small pelagic fish, squid and cuttlefish within their exclusive economic zones, or from exporting substantial quantities of fish (Table 4.5.4). Although revenues from licences and exports can boost purchasing power to buy food, there is concern that the focus on revenue has been at the expense of long-term economic development and food security (Trouillet *et al.,* 2011; Belhabib *et al.,* 2013, 2014).

Population growth is expected to result in a significant increase in demand for fish in West Africa. For example, twice as much fish will be needed by Benin and Liberia by 2050 (Lam *et al.,* 2012). Regrettably, present-day fisheries management, trade and distribution practices will not be able to deliver the fish required in the future (Delgado *et al.*, 2003, Béné and Heck, 2005). Modelling also indicates that there will be a shortfall in fish supply for all countries in West Africa due to climate change by 2050 (Lam *et al*., 2012).

Figure 4.5.9 Fishermen in Cape Verde off the western coast of the African continent. © Dyhia Belhabib.

Continued high GHG emissions are expected to increase the gap further (Figure 4.5.8) (Lam *et al.,* 2012), with the largest differences between forecasted demand for fish and projected fish catch occurring in Benin, Côte d'Ivoire, Nigeria and Western Sahara. Across the region, the potential reduction in total annual landings by the 2050s under a high emissions scenario is estimated to be 670,000 tonnes (i.e. a reduction of 26% compared to current levels) (Lam *et al.,* 2012). For the EEZs of the six countries located closest to the equator (Ghana, Côte d'Ivoire, Liberia, Togo, Nigeria and Sierra Leone), catches are projected to be reduced by around 50%. The projected decreases are due to the expected shifts in distribution of fish species in response to higher water temperatures, and a decrease in net primary productivity in the tropical region by the 2050s (Sarmiento *et al.,* 2004; Bopp *et al.,* 2013).

Reduced future landings of fish in West Africa are not only expected to have implications for food security, they will affect the economies of countries that are highly dependent on fish exports, such as Mauritania and Senegal. In this region, narrowing the gap in the fish needed for local food security and reducing the burden involved in importing fish will depend on rebuilding overfished or depleted stocks, reducing post-harvest losses and ensuring that a sufficient proportion of the region's rich small pelagic fish resources are allocated for local consumption (FAO, 2014a). It will also depend on increasing the currently low capacity of fishing communities (Belhabib *et al.,* 2016) to adapt to climate change (Figure 4.5.9).

4.5.3.5 Central and South America

Consumption of fish is relatively low in several Latin American countries (Flores, 2014) due to ready access to other animal protein and cultural preferences (Table 4.5.5). However, the region makes a substantial contribution to the global supply of fish, and the supply of fish meal for mariculture, freshwater aquaculture and animal husbandry (Gasalla and Castro, 2016). Overall, the wide variety of marine fisheries in the region, which range from the world's largest fishery (Peruvian anchovy) to squid fisheries in both the Pacific and Atlantic Oceans, to numerous small-scale coastal fishing activities, have yielded annual catches exceeding 10 million tonnes for several decades (FAO, 2016).

Harvests from the large fisheries in Peru and Chile, and fisheries in Brazil and Argentina, vary significantly from year to year, however, due to the profound effects of the El Niño Southern Oscillation (ENSO) (Bakun, 1993;

Table 4.5.5 Recent population, total fish catch and patterns of per capita fish consumption for selected countries in Latin America (source: FAO, 2014a; Flores, 2014).

Country	Population in 2012 (million)	Total fish catch in 2012 (tonnes)	National fish consumption (person^{-1} yr^{-1}) (kg)	Trend in fish consumption
Argentina	41,900,000	7380,00	5.0	Stable
Brazil	198,700,000	842,900	11.2	+ 6 kg in 10 years
Chile	17,460,000	2,572,881	6.4	Stable
Colombia	47,700,000	75,651	6.1	+2.1 kg in 6 years
Guyana	800,000	3,900	34.0	Stable
Honduras	7,930,000	8,300	3.5	Increasing
Mexico	120,800,000	1,581,579	13.2	Stable
Nicaragua	5,920,000	33,850	7.5	Stable
Panama	3,840,000	176,649	25	Stable
Perú	28,990,000	4,807,923	19.0	Increasing
Uruguay	3,400,000	76,162	6.0	Stable
Venezuela	29,950,000	213, 069	6.5	Increasing

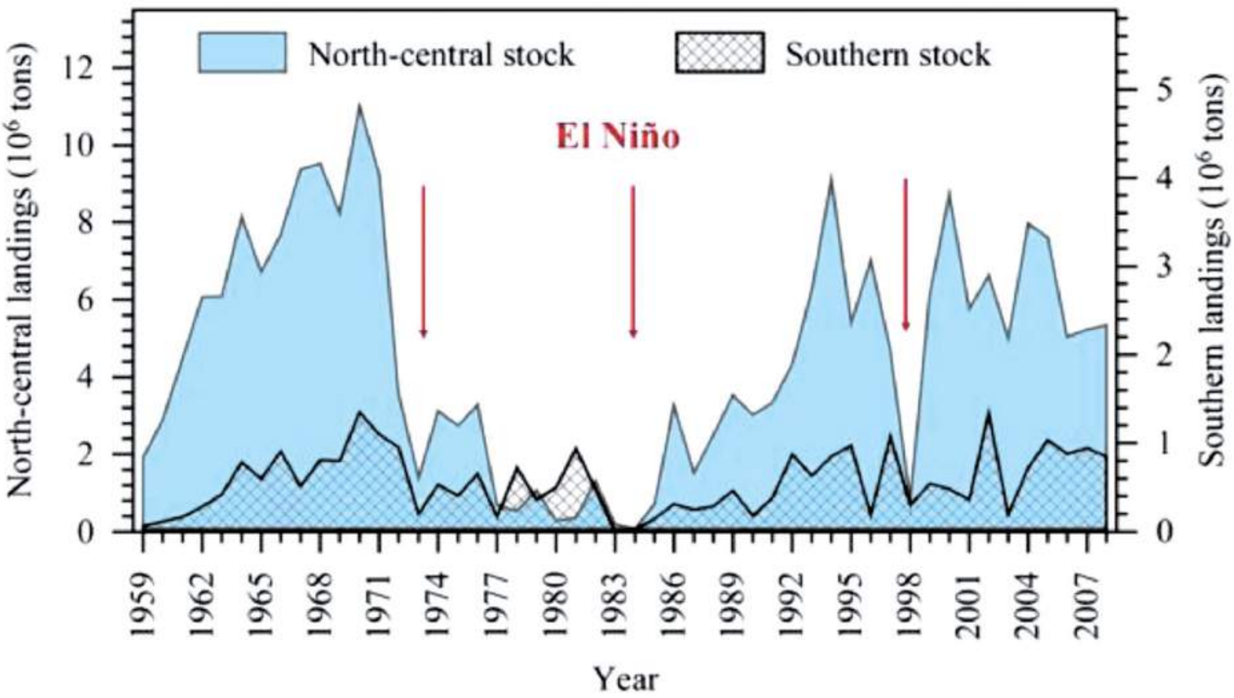

Figure 4.5.10 North-central and southern stock Peruvian anchovy landings between 1959 and 2008 in relation to El Niño events (source: IMARPE).

Sharp and McLain, 1993; Garcia *et al.,* 2004). This is illustrated best by the effects of ENSO on the production of Peruvian anchovy: catches fall dramatically during El Niño events when weakening of the south-east trade winds limits the upwelling of the nutrient-rich waters required to support a high biomass of this species, but increase dramatically when strong upwelling recommences under La Niña conditions (Daw *et al.,* 2009; Arias Schreiber *et al.,* 2011) (Figure 4.5.10). It remains to be seen whether ocean warming will change the effects of La Niña events on the Peruvian anchovy fishery and the strength of the upwelling involved. It is interesting to note, however, that Barange *et al.* (2014) project declines in fish production in Peru based on a model incorporating upwelling systems. Maximizing the sustainable benefits of this globally significant fishery will continue to depend on applying the various strategies identified to cope with great variation in abundance due to climatic variability (Arias Schreiber *et al.,* 2011).

In contrast, ocean warming and the knock-on effects on ocean circulation and stratification on primary production (Hoegh-Guldberg *et al.,* 2014) are expected to disrupt fishing patterns for a variety of other marine fisheries in the region. The effects of ocean warming are expected to be particularly strong in South Brazil and Uruguay (Popova *et al.,* 2016). Elsewhere, the impacts of ocean warming are expected to be mixed. For example, catches of 10 of the top 12 fish species caught in Mexico are projected to decline by 2050 under a high GHG emissions scenario (Sumaila *et al.,* 2014); landings by small-scale fisheries are projected to decrease in tropical areas as species move poleward in response to thermal stress (Cheung *et al.,* 2010) and sea-level rise reduces the extent of coastal fish nursery habitats (Costa *et al.,* 1994; Canziani *et al.,* 1998); Pacific and Atlantic sardines are expected to continue to move into cooler and deeper waters (Gasalla, 2012; Silva *et al.,* 2015); skipjack tuna are likely to be more abundant in the Inter-American Sea and other productive oceanic areas (Muhling *et al.,* 2015); and jumbo squid are expected to continue to be caught more commonly by Peruvian and Chilean small-scale fisheries (Rodhouse *et al.,* 2014).

The mixed responses of species to ocean warming in Central and South America will result in advantages for some countries and disadvantages for others. Artisanal fishers in Latin America dependent on coastal fish species for food and income are likely to suffer hardship where species move poleward, because the restricted mobility of fishers will prevent them from operating further afield to target the usual stocks. In other locations, there may be enhanced opportunities for livelihoods through creation of more sport fishing enterprises targeting increased abundances of species of interest to anglers.

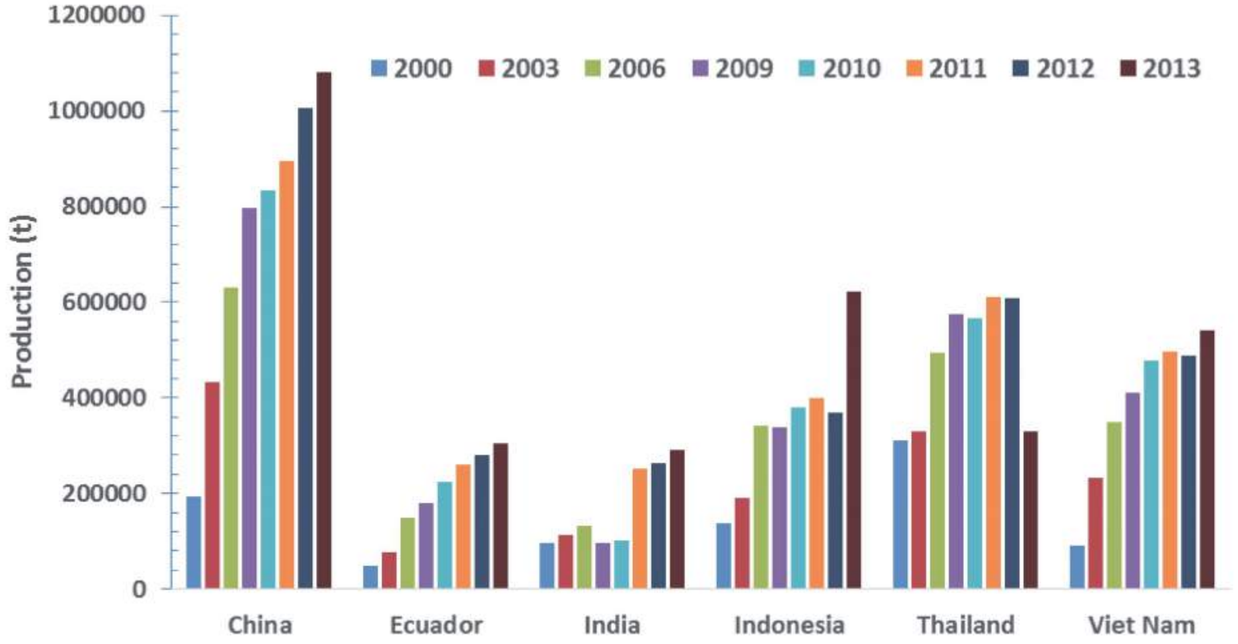

Figure 4.5.11 Trends in shrimp production, in selected years, in major producing countries from 2000 onwards (source: FAO, 2014b).

4.5.4 Effects on mariculture

For the past two decades, most mariculture production has occurred in the tropics and sub-tropics and been dominated by seaweed and molluscs (De Silva and Soto, 2009; FAO, 2014a). Substantial shrimp farming also occurs in tropical and subtropical coastal and estuarine areas (Ahmed and Diana, 2015) (Figure 4.5.11), supplying >70% of shrimp marketed globally (Benzie, 2009) (Figure 4.5.12). However, all shrimp culture depends on feeds containing fish meal.

The rapid development of aquaculture during recent decades is expected to continue, and will need to provide most of the increasing demand for fish (FAO, 2014a) (Figure 4.5.13). It remains to be seen whether more finfish will be produced through mariculture in the future – at present, only 10% of farmed finfish production occurs in coastal waters (FAO, 2016). Expansion of finfish aquaculture in fresh water will become increasingly difficult unless environmentally sustainable cage culture can be accommodated

Figure 4.5.12 Harvesting shrimp (*Penaeus monodon*), Chilaw, Sri Lanka. © Sena De Silva.

Figure 4.5.13 Intensive finfish cage culture in Xinqua Bay, Hainan Island, China. © Sena De Silva.

in water bodies impounded for other purposes – a process that has already begun in some developing countries (Abery *et al.,* 2005; Blow and Leonard, 2007; De Silva and Phillips, 2007). But mariculture of finfish also faces limitations because low-cost farming methods are largely restricted to sheltered coastal areas. Although technology and computer simulations exist for offshore expansion of mariculture by anchoring large sea cages in open ocean areas (Duarte *et al.,* 2009), such developments are often likely to be beyond the financial resources of developing nations, which have the greatest needs for fish. Nevertheless, it is perhaps inevitable that the proportion of farmed finfish produced by mariculture will need to increase.

Recent assessments indicate that ocean warming can be expected to affect plans to expand mariculture both directly and indirectly (De Silva and Soto, 2009; De Silva, 2012b). The main direct impacts are likely to be caused by alterations in the suitability of areas for growing particular species, driven by higher water temperature.

Fish mariculture in temperate regions, where much of the present-day production occurs (Halwart *et al.,* 2007), is expected to be affected negatively by ocean warming. Salmon farming and the emerging culture of cod *Gadus morhua* need to operate within a relatively narrow range of temperatures for optimal performance. Temperatures >17 ºC would be detrimental to salmon and cod farming because feed intake drops and feed utilization efficacy is reduced above this threshold (Anon., 2008).

Changes are also expected to occur in prime locations for farming tropical and sub-tropical marine finfish, such as groupers, snappers and cobia, as water temperatures increase. Where temperatures begin to exceed the thermal optima for these species, mariculture operations will need to move to higher latitudes.

The effects of a warmer ocean, manifested through changes in current patterns, and in salinity, run-off of nutrients and dispersal of pollutants resulting from higher rainfall, are also likely to reduce the productivity of other mariculture operations in tropical areas. For example, abrupt changes in salinity and alteration of coastal currents can be expected to affect recruitment of wild post-larvae collected for grow-out (World Bank, 2000; Ahmed *et al.,* 2013).

One of the main indirect effects of ocean warming on mariculture is expected to be more frequent disease outbreaks arising from redistribution of existing pathogens and increased virulence of previously dormant pathogens (Harvell *et al.,* 1999; Mennerat, 2010; Altizer *et al.,* 2013; Leung and Bates, 2013; Chadag, 2014) (Table 4.5.6). The recent effects of early mortality syndrome on shrimp farming (FAO, 2013) provide another insight into the economic losses that can occur as a result of mariculture diseases. The incidence of ice–ice disease during farming of seaweed *Kappaphycus alvarezii* ('cottonii') and *Eucheuma denticulatum* ('spinosum') has also increased recently in north-east Sulawesi, Indonesia (Aslan *et al.,* 2015). Factors that predispose seaweed to this disease include changes in temperature, salinity, light intensity, and colonization by bacteria, fungi and epiphytes (Largo *et al.,* 1995a,b; Largo, 2002; Solis and Draeger, 2010).

Another indirect threat to mariculture from warmer, more nutrient-rich, coastal waters is that the frequency of harmful

Table 4.5.6 Aquatic diseases prevalent in tropical countries and their relationship with some of the key elements of climate change (source: Mohan, 2015)

Disease	Description and sensitivity to climate change
Infection with *Aphanomyces invadans* (Epizootic Ulcerative Syndrome-EUS)	Fish fungal disease. Seasonal disease of wild and farmed freshwater and estuarine fish; grows best at 20-30 C; salinity over 2 ppt can stop the spread, 97 species of fish confirmed to be susceptible; no data available on vectors; transmission horizontal; outbreaks normally associated with cooler months of the year and after rainfall.
Koi herpes virus disease (KHVD)	Fish viral disease. Reported both in tropics and temperate regions; common carp and varieties of this species like koi are most susceptible; disease pattern influenced by temperature; occurring between 16 and 25°C.
Viral Encephalopathy and Retinopathy (VER)	Fish viral disease. Serious disease of mainly marine fishes; reported from more than 50 species; water most important abiotic vector; reported in both tropics and temperate regions; outbreaks related to water temperature.
White Spot Disease (WSD)	Shrimp viral disease. Wide host range, especially decapod crustaceans, in marine, brackish and freshwater systems; horizontal and vertical transmission, outbreaks induced by rapid changes in salinity; temperature has profound influence on disease outbreaks with temperatures of 16-30°C conducive for outbreaks; stocking in cold season is one of the predisposing factors of WSD outbreaks.
Infectious Myonecrosis	Shrimp viral disease. Temperature and salinity effects are considered to be predisposing factors to disease outbreaks
White tail disease	Viral disease of freshwater prawn. Penaeid shrimp and aquatic insects are vectors; rapid change in salinity, temperature and pH are predisposing factors to disease outbreak.
Shrimp AHPND	Emerging bacterial disease of shrimp. Caused by pathogenic strain of *Vibrio parahaemolyticus*; reported from Asia and Latin America; nutrient loading and water quality as predisposing factors.
Fish ectoparasites like protozoans, flukes, crustaceans (*Argulus*, *Lernaea*)	Life cycle and larval development influenced by water temperature.
Streptococcus infection in fishes	Diverse host range; higher temperatures (>30°C) predisposes fishes like tilapia to outbreaks of *Streptococcus* infection.

algal blooms (HABs) could increase (Peperzak, 2003; Edwards *et al.,* 2006; Al-Azri *et al.*, 2015). HABs pose a threat to human health through consumption of filter-feeding molluscs, resulting in what is commonly called 'shellfish poisoning'. The effects of HABs can also be expected to dislocate local benefits from mariculture, e.g. employment.

Possible shortages in the supply of fish used to make the fish meal and fish oil ingredients in mariculture feeds (De Silva and Soto, 2009) is one potential indirect impact not expected to unduly disrupt the expansion of marine fish farming. Recent modelling suggests that technological developments should reduce the dependence of mariculture on fish meal (Merino *et al.,* 2012; Barange *et al.,* 2014).

4.5.5 Global assessments for marine capture fisheries

Recent assessments of the future status of marine fish stocks include not only studies examining the projected effects of climate change but also those focusing on the possible effects of improvements in management. For example, Costello *et al.* (2016) examined more than 4,700 fisheries worldwide, representing 78% of reported global fish catch, and concluded that: 1) the median fishery is in poor health; 2) only 32% of fisheries are in good biological condition; 3) applying sound management reforms could generate annual increases in global catch exceeding 16 million tonnes; and 4) appropriate reforms could result in rapid recovery, with the median fishery taking less than 10 years to reach target levels. In short, common-sense reforms to fishery management could improve overall fish abundance and increase food security and profits. However, as useful as such assessments are, the proposed improvements in management may be of limited value unless they also integrate the likely effects of climate change from global assessments, like those described below (Schindler and Hilborn, 2015).

Global assessments of future fish production that include climate change as a driving factor, confirm the patterns from the five developing country regions – there will be winners and losers (Weatherdon *et al.,* 2016). Thus, the scope for increased catches outlined by Costello *et al.* (2016) can be expected to vary among locations. As a general rule, global assessments project losses of fish species and decreased fisheries production in tropical areas and increases in higher latitude temperate areas (Allison *et al.,* 2009; Cochrane *et al.,* 2009; Cheung *et al.,* 2011; Blanchard *et al.,* 2012; Barange *et al.,* 2014; Jones and Cheung, 2015).

However, differences occur among assessments, depending on the modelling approach used, when projections are downscaled to regional or national levels, highlighting differing uncertainties among models. For example, Barange *et al.* (2014) project a different pattern of winners and losers among West African countries than those described in para. 4.5.3.4. Use of ensemble modelling approaches promises to help reduce such inconsistencies and quantify the uncertainties relating to projections of fisheries production due to climate change and, ultimately, help build confidence in using these projections for policy discussion (Jones *et al.,* 2012; Jones and Cheung, 2015; Cheung *et al.,* 2016b). For example, the Fisheries and Marine Ecosystem Model Intercomparison Project (FISH-MIP) seeks to collate global research efforts to compare global and regional projections of living marine resources and fisheries. It aims to standardize model inputs, where possible, and compare outputs from multiple models to assess climate and fisheries impacts on marine ecosystems and the services that they provide.

4.5.6 Implications for food security

From the evidence summarized above, there is every reason to believe that ocean warming will reduce or redistribute the benefits of marine fisheries and mariculture in those regions of the world with a high dependence on fisheries for food security and livelihoods (Figure 4.5.14).

All four dimensions of the contributions of marine fisheries and mariculture to food security will be affected (Cochrane *et al.,* 2009). The *availability* of fish will vary as a result of changes in fish habitats, fish stocks and the distributions of species. The s*tability* of supply will be altered by changes in seasonality, increased variance in ecosystem productivity and increased variability in catches. *Access* to fish will be affected by changes in opportunities to derive livelihoods from marine fisheries and mariculture, *utilization* of fish will be affected because some communities will need to adjust to species not consumed traditionally, and increased prevalence of aquatic diseases and HAB are likely to render some fish production inedible more frequently.

The effects on food security are likely to be greatest in tropical and subtropical countries where the largest reductions in fisheries production are generally expected to occur. However, as profound as the effects of ocean warming on productivity of marine fisheries are likely to be in many of these countries, population growth and

Figure 4.5.14 Fishers sorting their nets near Honiara, Solomon Islands. © Johann Bell.

the quality of resource management will probably have a much greater influence on availability of fish per capita for the next few decades (Para. 4.5.3). This implies that governments must identify effective ways of minimizing and filling the gap between the amount of fish readily available and the quantities of fish required for good nutrition of national populations.

4.5.7 Recommended adaptations

The main adaptations to reduce the gap in supply of fish for food security involve instituting better management of fish habitats and fish stocks (Figure 4.5.15), and improving supply chains. To fill the gap, governments will need to ensure that mariculture (and freshwater aquaculture) continue to develop in environmentally

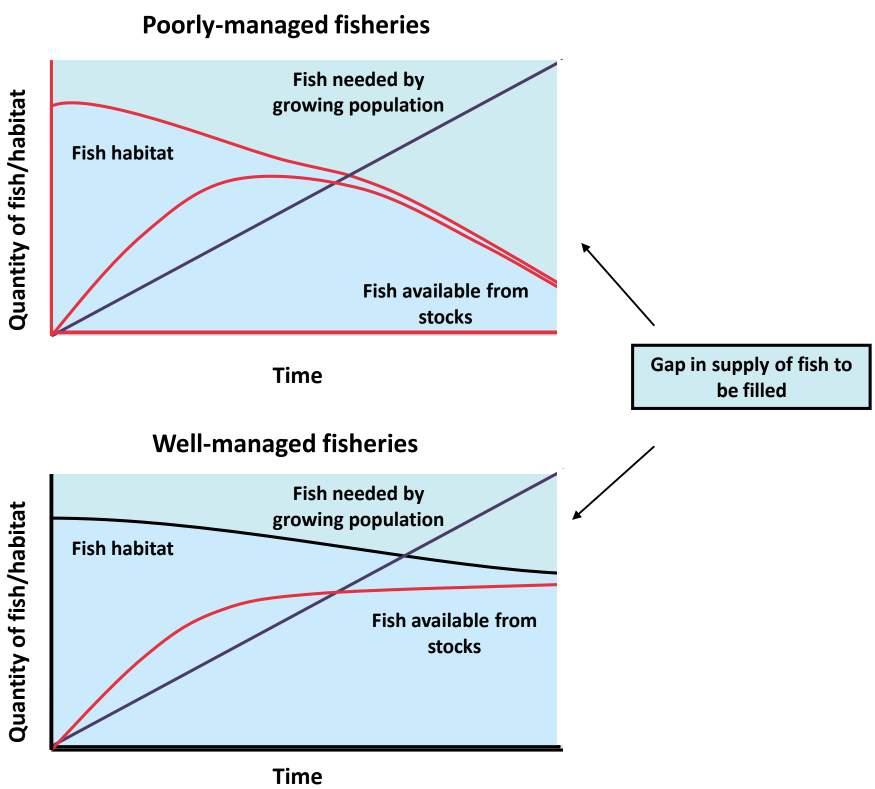

Figure 4.5.15 The importance of managing fish habitats and fish stocks well to minimize the gap between the fish required for good nutrition of populations and sustainable harvests of fish (source: Bell *et al.*, 2011b).

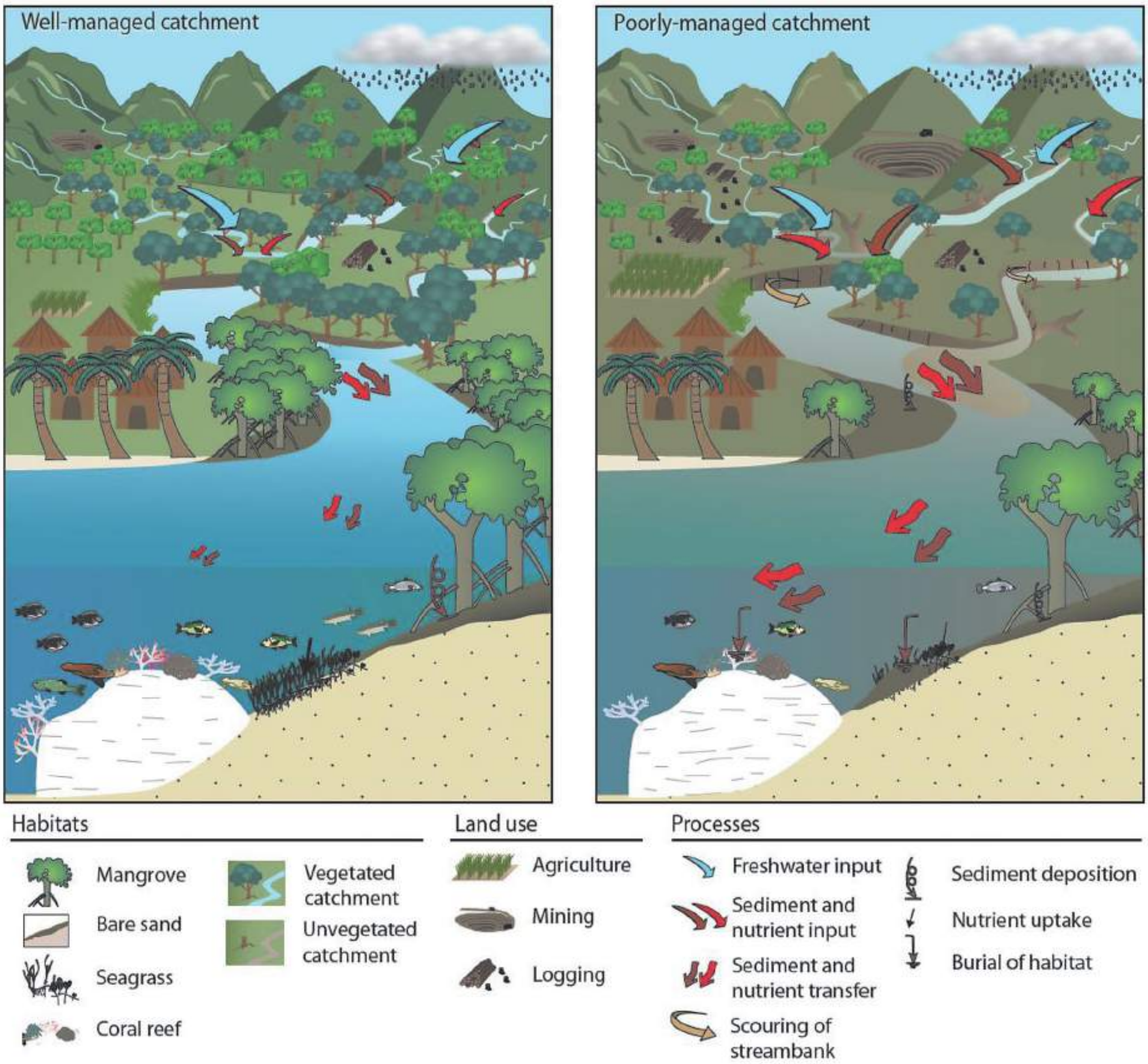

Figure 4.5.16 Differences in the quality of coastal fish habitats when catchments are managed well or managed poorly (source: Bell *et al.,* 2011c).

sustainable ways (De Silva and Soto, 2009; De Silva, 2012b; Hall *et al.,* 2011; FAO, 2014a) and, where necessary, reallocate some of the fish normally traded (either as exports or through sale of licences to DWFNs) to domestic consumption.

4.5.7.1 Adaptations to reduce the gap

Where they are currently weak, improvements in the following two broad categories of management will help to reduce the gap by optimizing fisheries production.

1. Reducing the impact of local stressors on fish habitats. For example, restoring catchment vegetation to minimize the effects of run-off of sediments and nutrients on coral reefs, mangroves and seagrasses (Figure 4.5.16). The need for such integrated coastal management and marine spatial planning is widely recognized (Sale *et al.,* 2014), and may extend to constructing artificial habitats to increase the capacity of coastal environments for fish recruitment. Integrated coastal management is now imperative to reduce the negative effects of coastal development on fisheries production and the incidence of HABs.
2. Keeping production of fisheries within sustainable bounds using the most appropriate management measures for the national context and an ecosystem approach that integrates the effects of climate change (Heenan *et al.,* 2015; Samoilys *et al.,* 2015). For many developing countries, this will depend on primary fisheries management

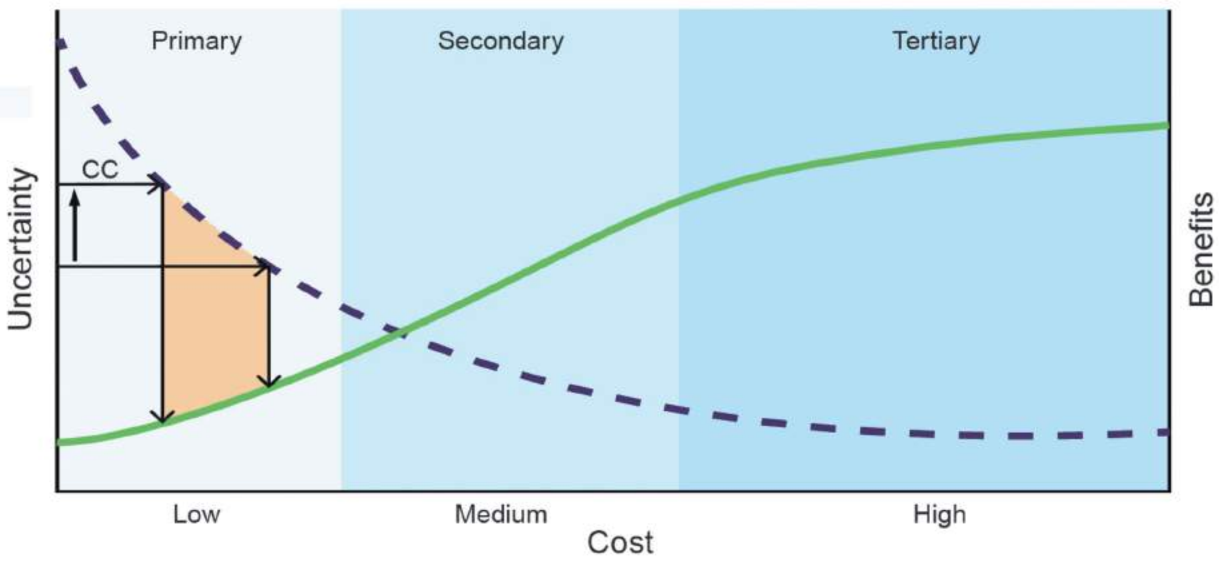

Figure 4.5.17 General relationship between potential benefits from fisheries (green line), and uncertainty in information for management (blue line), as functions of costs, for primary, secondary and tertiary fisheries management (source: Cochrane *et al.,* 2011 and Bell *et al.,* 2011c). The reduction in benefits under primary fisheries management as a result of the increased uncertainty caused by ocean warming and other features of climate change (CC) is indicated by the orange shading.

(Cochrane *et al.,* 2011)[3], which will need to become progressively more precautionary as the ocean continues to warm (Figure 4.5.17) and be well enforced (Samoilys *et al.,* in press). Climate-informed, primary fisheries management will involve raising awareness of the alterations in fish distribution and abundance due to ocean warming and diversifying fishing practices to take catches representative of the changes in relative abundance of species (Cheung *et al.,* 2013b). For coral reef fisheries, herbivorous fish species are expected to comprise a higher proportion of the catch in the future (Pratchett *et al.,* 2011). However, harvesting of herbivorous fish will need to be restrained to ensure they remain plentiful enough to help remove the algae that inhibit the survival and growth of corals (Bellwood *et al.,* 2004).

Improvements to supply chains, from beginning to end, can also help fill the gap by making fishing more efficient and reducing waste. Environmental forecasting of the best times to fish (and the onset of extreme events) via mobile phone networks can reduce travel/search times for small-scale fishers and enhance diversification of livelihoods into farming activities when fish are harder to catch. Mobile phones can also be used to assess market conditions to optimize income and arrange the timing of transport to markets. Improving fish handling, by providing better access to ice, for example, will increase the time that catches remain fit for human consumption.

4.5.7.2 Adaptations to fill the gap

Increasing environmentally sustainable mariculture (and freshwater aquaculture) is one of the most important adaptations to the effects of ocean warming on the availability of fish for food security. The following steps will be particularly important:

- improving national capacity by providing the necessary technical knowledge, extension services and incentives to scale-up the production of juvenile fish for grow-out and increase the number of fish farms;
- continuing the research needed to develop suitable feeds for marine finfish with minimal fish meal and fish oil content, including exploration of the best ways to incorporate fish processing waste into feeds;
- commencing more genetic improvement programmes to build the resilience of domesticated species to higher SST and pathogens expected to be favoured by ocean warming;

3 Primary fisheries management recognizes the need to use simple harvest controls, such as size limits, closed seasons and areas, gear restrictions and protection of spawning aggregations. In many cases it can be applied most effectively through community-based approaches (Govan *et al*., 2008; SPC, 2010; Rocliffe *et al*., 2014). Secondary and tertiary fisheries management require greater investments in stock assessments to reduce uncertainty about the economic benefits that can be gained from more accurate and precise estimates of sustainable harvests.

- exploring the scope for domestication of additional marine fish species (preferably omnivores) with promising attributes for hatchery rearing, tolerance of higher temperatures and rapid growth in culture systems;
- promoting the capture and culture of wild-caught post-larvae of species that have high post-settlement mortality but good survival in culture (Hair *et al.,* 2002), provided such harvests do not have adverse effects on recruitment to capture fisheries;
- encouraging stock enhancement of coastal species where it has been demonstrated that release of culture juveniles adds value to other forms of management (Bell *et al.,* 2005b; Lorenzen *et al.,* 2010); and
- growing-out bycatch species, as done in India (pers. comm. S. Shyam, CMFRI), in ways that address risks of overfishing as a result of this practice.

Despite the great need to increase aquaculture production (Merino *et al.,* 2012), for several developing countries the most practical ways of filling the gap in fish supply will be increasing access to large and small pelagic fish presently caught mainly by industrial fleets. Options available to governments include:

- Assisting small-scale coastal fishers to transfer some of their fishing effort to pelagic fish by equipping them to fish safely and effectively further from shore and expanding the use of nearshore fish aggregating devices (Bell *et al.,* 2015b) (Figure 4.5.18). Such investments not only increase access to fish now, they will help communities adapt to the negative effects of ocean warming on the productivity of fisheries associated with coral reefs (Bell *et al.,* 2013). Even where tuna are projected to decline within EEZs as the ocean warms (Para. 4.5.2), tuna are still expected to be abundant enough to make these adaptations effective.
- Implementing policies that: 1) ensure that industrial fishing operations do not have negative effects on small-scale fishers, 2) require industrial fleets to land bycatch, and target species if necessary, at major ports to provide urban communities with low-cost fish, and 3) facilitate the development of small and medium enterprises to distribute fish to urban and peri-urban areas (Bell *et al.,* 2015a). In many cases, the fish to be retained for local food security can be offloaded during routine transhipping operations and may only be a small proportion of the total industrial catch. For example, only 3% of the tuna catch in Papua New Guinea would be needed for coastal and urban communities to have access to the recommended quantities of fish for good nutrition by 2020 (Table 4.5.1). Although reallocation of a small percentage of the recommended tuna from the waters of PNG for direct domestic consumption is likely to result in a small economic loss, the benefits to public health are expected to be substantial (Golden *et al*., 2016). Quantifying this trade-off will assist governments to implement the best food security policies for adapting to the effects of ocean warming on fisheries resources.

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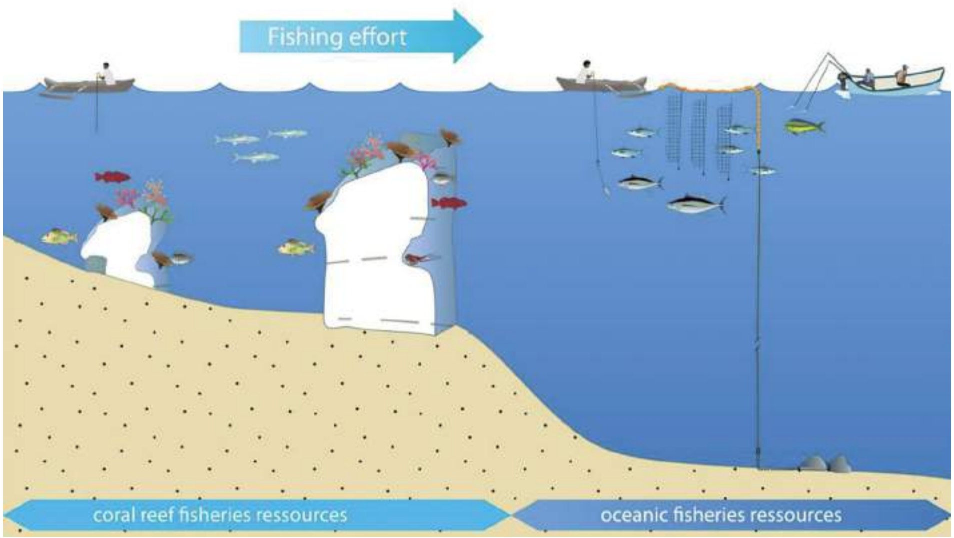

Figure 4.5.18 Nearshore fish aggregating devices allow some coastal fishing effort to be transferred to pelagic (oceanic) fisheries resources (source: SPC, 2014). (However, managers should ensure that no net increase in the overall catch of oceanic fisheries resources occurs by reducing industrial catches to cater for the needs of small-scale fishers).

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