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Preliminary Assessment of the Effects of Climate Change on Fisheries and Aquaculture in the Pacific

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1. Introduction

This brief report outlines how the climate of the Pacific is projected to change, how climate change has affected fisheries elsewhere in the world, and how it is expected to affect fisheries and aquaculture in the Pacific. The emphasis is on the implications for economies of Pacific Island Countries and Territories (PICTs). It concludes with general recommendations that should help the regional and national management agencies and other stakeholders in fisheries to adapt to maintain the benefits of fisheries.

The assessments of the projected effects of climate change, and the recommended approaches for adaptation, are preliminary. They are derived from the early phases of a major regional project to assess the vulnerability of fisheries and aquaculture in the Pacific to climate change coordinated by SPC and supported by AusAID[1]. The project is due to be completed by mid 2010 and will deliver a much more comprehensive assessment of likely impacts, practical adaptations, and investments needed to address key gaps in knowledge.

2. A changing climate and ocean

The build-up of carbon dioxide (CO_2) and other greenhouse gases in the atmosphere due to human activities is acting in two major ways that will ultimately affect fisheries and aquaculture in the Pacific – global warming and ocean acidification.

The accumulation of greenhouse gases is trapping more of the heat that previously escaped from the earth, leading to an overall increase in average global temperature (Meehl et al. 2007). For the low emissions (B1) and high emissions (A2) scenarios outlined in the 4th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2007), the projected increases in surface atmospheric temperature in the Pacific region by 2035 range from 0.5 to 0.8 ^{0}C, but increase considerably for both the B1 and A2 scenarios by 2100 (Table A1). The oceans will absorb much of this heat (see projected increases in sea surface temperature for the Pacific in Table A1). Thermal expansion of the oceans, together with melting of glaciers and land ice, results in rising sea level, which is projected to increase by up to 50 cm by 2100 under the A2 scenario (Table A1). However, this may well be an underestimate due to accelerated melting of land ice (Bindoff et al 2007). Increases in ocean temperature also make the surface waters more stable, reducing vertical mixing and the

[1] For details see http://www.spc.int/sppu/index.php?option=com_content&task=blogcategory&id=1&Itemid=80

availability of nutrients in the upper level of the ocean. Reductions in the supply of nutrients limit the primary production at the base of the food chains supporting fisheries.

A warmer global climate also causes changes in atmospheric and oceanic circulation patterns giving rise to regional changes in climate. Tropical cyclones are a major source of disturbance to coastal environments in the tropical Pacific and although there may be fewer cyclones in a warmer world, those that do occur are likely to be more intense, resulting in rougher seas, more powerful waves, stronger winds, more intense rainfall and greater localized destruction (Poloczanska et al 2007, CCSP 2008, Fabricius et al. 2008). As tropical oceans warm, there will be greater evaporation and moisture availability leading to an intensification of the hydrological cycle and expansion of the Hadley Circulation in the Pacific. Total rainfall is projected to increase in the tropical Pacific between 10^{o}N to 10^{o}S and decrease in the subtropics (Table A1).

El Niño-Southern Oscillation (ENSO) events are the major source of interannual climate variability in the region, with distinct oceanographic, temperature, rainfall and cyclonic conditions associated with the two phases: El Niño - when the equatorial divergence is located well to the east of the Pacific, and surface waters are warmer than usual, and La Niña – when the equatorial divergence occurs across much of the region and temperatures are cooler. The divergence brings nutrient-rich waters to the surface and enhances the production of phytoplankton and zooplankton that supports fisheries. Global climate models do not, at present, provide a consistent picture as to how the occurrence, intensity or frequency of ENSO events might change with continued global warming. However, they do indicate that ENSO events will continue to be a dominant feature of Pacific climate for the foreseeable future.

Table A1.
Projected Changes to Features of the Pacific Climate and Oceans Relative to 1980-1999 Levels, Together with Projections of Total Concentration of Atmospheric CO_2

Climate feature	Low emissions (B1) scenario 2035	High emissions (A2) scenario 2035	Low emissions (B1) scenario 2100	High emissions (A2) scenario 2100
Surface atmospheric temperature (^{0}C)	0.5-0.8	0.5-0.8	1.0-1.5	2.5-3.0
Sea surface temperature (^{0}C)	SST changes are similar to those for surface temperatures though slightly lower in magnitude; there is also a spatial pattern to the projected surface warming with greater warming in the eastern than in the western equatorial Pacific and less warming in the SE Pacific			
Sea level rise (cm)*	8	8	18-38	23-51
Rainfall	5-15% increase in tropics, decreases in subtropics	5-15% increase in tropics, decreases in subtropics	10-20% increase in tropics, decreases in subtropics	10-20% increase in tropics, decreases in subtropics
Cyclone frequency and intensity	Cyclones less frequent but more intense. Projected to increase in intensity by 6-12% by 2100, equivalent to 0.5 of a cyclone warning category			
ENSO	ENSO events will continue as a source of interannual climate variability, but it is uncertain whether they will increase in frequency or intensity			
Aragonite saturation levels in ocean	Adequate to marginal for coral reefs	Adequate to marginal for coral reefs	Marginal	Low to risky for coral reefs
CO_2 (ppm)	~400	~400?	450-500	750-800

Source: Information on rainfall, temperature, tropical cyclones & ENSO - prepared for the SPC project by Dr GA Meehl, National Center for Atmospheric Research, USA following Meehl et al. (2007); sea level - Bindoff et al. (2007), CO_2 concentrations - Foster et al (2007); and aragonite saturation states - Guinotte et al (2003).
*Could be underestimates, depending on rate at which land ice and glaciers melt

In addition to changing atmospheric and oceanic climates, the increased burden of the main greenhouse gas, CO_2, is changing ocean chemistry – a process called ocean acidification (Hoegh-Guldberg et al 2007). The ocean has absorbed about a third of the human CO_2 emissions since around 1750 and it is now more acidic than at any time during the last 650,000 years (Orr et al. 2005). This effect is largely independent of global warming and has grave consequences for marine life. The dissolved CO_2 reacts with sea water to form weak carbonic acid, which reduces availability of the dissolved carbonate required by many marine calcifying organisms to build their shells or skeletons (Poloczanska et al 2007; Guinotte and Fabry 2008). There is serious concern that continued emissions of CO_2 will drive sufficient gas into the oceans to cause under-saturation of carbonate. Where this happens, the environment will not favour formation of structures like coral reefs created by animals and plants with carbonate skeletons and shells. The Pacific Ocean is projected to become more acidic by 0.3-0.4 pH units by 2100, reducing the supersaturation levels of aragonite (a form of carbonate) from >4 to 3.0-3.5 by 2070 throughout much of the tropical and subtropical Pacific (Guinotte et al. 2003), causing many coral reefs there to collapse (see Section 4.2).

Some of these projected changes in the climate system are already evident in the observational records. The pH of the oceans has fallen by 0.1, global sea level has risen by ~20 cm, and global average temperatures are now ~0.7^{o}C warmer than at the end of the 19th century (IPCC, 2007). There is also evidence of recent acceleration in the rate of these changes in the physical environment. This rate of change is of considerable concern when considering the impacts of a warming world on natural ecosystems, such as the fisheries of the tropical Pacific. Over the period 1950-2007, global average land and sea temperatures have warmed at 0.12^{o}C/decade and tropical Pacific sea surface temperatures at 0.07^{o}C/decade.

3. Effects of climate change on fisheries worldwide

There is broad concern around the world about the effects that future changes to climate will have on fisheries and aquaculture. This concern arises because even recent variations in climate on time scales of years to decades have caused significant variation in fisheries production. For example, catches of Peruvian anchovies varied from < 100,000 tonnes to > 13 million tonnes between 1970 and 2004 as a result of changes in ENSO (Brander 2007). Closer to home, we now know that the alternate phases of the ENSO cycle largely determine the distribution of skipjack tuna in the western and central Pacific Ocean - they move further east during El Niño years and then follow the warm pool west during La Niña episodes (Lehodey et al. 1997, Lehodey et al. 2003, Loukos et al. 2003). In other cases, abrupt changes in physical oceanography and biology, known as ‘regime shifts’ which can persist for more than a decade, have major consequences for the species composition and productivity of fisheries (Lehodey et al. 2006, Brander 2007). The effects of such shorter-term changes in climate are not always negative - a period of ocean warming around Greenland starting in 1925 resulted in a northern extension in the range of cod by > 1000 km and creation of an international fishery of up to >400,000 tonnes per year (Brander 2007).

In view of these often dramatic effects, fisheries managers are confronted by many important questions. Will the species that currently support fisheries still be available as greenhouse gases increase? If not, which species are most likely to replace them? For those species that continue to support fisheries, will climate change reduce the capacity for replenishment and production and increase the risk of overfishing? What costs will be involved in adapting to harvest fish in different ways? Will fishing at sea become more hazardous?

Concerted efforts in some parts of the world to answer such questions are now documenting how the observed and projected changes to atmospheric climate and the oceans are affecting, or are likely to affect, the distribution and production of fish, and the fisheries that depend on them (Perry et al. 2005, Hobday et al. 2006, Lehodey et al. 2006, FAO 2007, Brander 2007, Johnson and Marshall 2007, Poloczanska et al. 2007, Munday et al. 2008a).

3.1 *Effects on distribution of fish*

Alterations to water temperature, depth of the surface mixed layer and currents occurring as a result of changes in climate are having significant effects on the distribution of both oceanic and coastal fish. The main patterns that have emerged are: 1) expanded distributions of warm water fish species towards the poles (Parker and Dixon 2002; Perry et al. 2005), 2) latitudinal shifts in areas where species occur (Munday et al. 2008a), and contracted distributions of species adapted to cooler waters (Welch et al. 1998).

Other effects of climate change are also altering the patterns of fish distribution. These include: expansion of zones of low productivity (Polovina et al. 2008), which oceanic fish avoid in their search for food; 2) occurrence of key prey species at increasingly higher latitudes (Richardson 2008), which help support the food chain for oceanic fish where it was inadequate previously; and 3) changes to the strength of currents, which affect dispersal of fish larvae and connectivity among populations in different areas (Munday et al. 2008a).

3.2 *Effects on production of fish*

Climate change can be expected to mediate fish production through effects on reproductive success, recruitment processes, survival and growth of target species and/or their prey. These effects occur both directly, due to inherent sensitivities of marine organisms to changing environmental conditions, and/or indirectly through the influence of climate change on the habitats that support fish or the pathogens that can control their abundance (Brander 2007, Munday et al. 2008a). Collectively, these effects can flow on to fisheries productivity; Klyashtorin and Lyubushin (2005) showed that changes in long-term dynamics of 12 important commercial Atlantic and Pacific fish stocks mirrored long-term changes in sea-air temperature and atmospheric circulation.

Reproduction of fish is often highly sensitive to fluctuations in temperature (Munday et al. 2008a) and so warming can have either a positive or negative effect on egg production, depending on whether the target fish species is close to its thermal optimum. In general, most fishes are strongly adapted to the range of environmental conditions that they experience throughout the year. Rapid or dramatic increases in temperature above normal maximum temperatures are expected to have significant negative effects on overall viability of some fish populations (Munday et al. 2008b).

Interactions between the effects of higher water temperatures, altered currents and changes to the depth of the mixed layer on the dispersal and survival of larvae (Green and Fisher 2004, Meekan et al. 2003, Poloczanska et al. 2007), are expected to result in new patterns of recruitment. As a result, the areas with the potential to yield the most fish within the distribution of a species can be expected to change. Evidence is also emerging that acidification of the ocean can disrupt the olfactory cues used by fish larvae to settle successfully on coral reefs (Munday et al. 2009), raising concerns that the inherently large variation in recruitment success may become even more extreme. Both effects have implications for fisheries as they can be expected to alter the location of the best fishing grounds.

The area and structural complexity of the coral reefs, seagrasses and mangroves that provide shelter and food for many coastal fish species are likely to be altered by rising water temperature, acidification of the ocean, more intense cyclones, changes in sedimentation from new patterns of rainfall and rising sea levels (Poloczanska et al. 2007). The coverage and quality of these key structural habitats have already been reduced dramatically worldwide through the impacts of developments in the coastal zone (Duarte 2002, Alongi

2002). The concern is that climate change will create damaging synergies with localised non-climate stressors, and exacerbate the problem (Hoegh-Guldberg et al. 2007, Johnson and Marshall 2007).

Increasing temperatures are also expected to have a direct effect on the growth of fish, especially for temperate species in which growth is currently limited by cold winter temperatures (Thresher et al. 2007).

The relative importance of these various processes is yet to be determined. In some locations, the impact of any increased production of existing target species may be overshadowed by the alterations to species composition likely to occur as a result of changes to fish distribution and modification of habitats.

4. Potential impact of climate change on fisheries and aquaculture in the Pacific

Preliminary assessments indicate that the oceanic, coastal and freshwater fisheries, and aquaculture operations, of the Pacific will be as equally subjected to the direct and indirect effects of climate change as fish resources elsewhere in the world. A summary of the main potential positive and negative effects of climate change on fisheries and aquaculture in the region is provided below.

4.1 *Changes to the distribution and abundance of tuna*

Alterations in ocean temperatures and currents, and the food chains in the open ocean, are projected to affect the location and abundance of tuna species (Lehodey et al. 1997, 2003, Loukos et al. 2003). Initial modeling indicates that the concentrations of skipjack and bigeye tuna are likely to be located further to the east than in the past (Lehodey et al., 2008a,b; Lehodey et al., in press). The simulations have yet to be done for yellowfin and albacore.

Although the current patterns of abundance of tuna are mediated strongly by ENSO (Lehodey et al. 1997), the quantities of tuna likely to be available to each PICT during El Niño and La Niña events are relatively well understood and are used by PICTs in consultation with regional agencies to plan contributions to economic growth through provision of access rights to distant water fishing nations (DWFNs). They are also taken into account in proposals to attract investment for the development of domestic fishing fleets and the establishment of local canneries, loining plants and export businesses.

Significant changes to the distribution of tuna will make the Exclusive Economic Zones (EEZs) of some PICTs more, or less, attractive to DWFNs engaged in the surface fishery for skipjack tuna, with consequences for national GDP. As it stands, revenues from the sale of fishing rights for tuna currently make up a far greater proportion of GDP in some of the smaller PICTs in the central Pacific (e.g., Kiribati, Tuvalu, Tokelau) than they do for many countries further to the west (Table ### in main report). Displacement of tuna stocks further east in the Pacific would be a windfall for these PICTs because they currently have few other options for generating national income. Their GDP would increase substantially in relative terms, especially if prices increase due to depressed catches elsewhere in the world.

Reduced demand by DWFNs to fish for skipjack tuna within the EEZs of PICTs in Melanesia will have a far lower impact on their GDP in relative terms - revenue from access fees currently makes only a minor contribution to their larger economies (Table ###). Nevertheless, there will be substantial losses in real terms given the large quantities of tuna currently caught there, particularly during La Niña episodes. The negative effects on other PICTs in the western and central Pacific (FSM, Nauru) are likely to be more severe.

The consequences of skipjack tuna moving further east over time may have some negative effects on the viability of canneries in the western Pacific. Currently, the canneries in Melanesia use fish caught within their EEZs and pay ~US$150 per tonne less for fish than their competitors in Thailand, which have to meet higher costs for the delivery of their raw materials. However, if the canneries in Melanesia have to source some of their fish from further east, this comparative advantage could be reduced substantially because the costs per tonne for delivery by reefers are not directly proportional to distance - there is a large fixed cost for charter and demurrage.

Another consequence of skipjack tuna moving further east is that operators in the fishery in the Philippines, which is already heavily exploited and has some overcapacity, will seek to follow the resource. As the Philippine industry usually operates close to shore bases, this may provide opportunities for, or conflict with, plans by PICTs to domesticate the tuna sector.

The changes in the distribution of skipjack tuna will happen progressively over many years, giving the industry time to adapt. A potential complicating factor is the spectre of future rises in the cost of fuel. This subject is covered in Appendix ###.

Identifying the preliminary implications of climate change for longlining operations is not practical at this stage because although initial simulations indicate that there will also be an eastward shift in adult bigeye tuna (Lehodey et al. 2008), modelling for yellowfin tuna and albacore is not yet available. Given the great value of the longline fishery, and the fact that it is the main way that tuna currently contribute to the economic growth of PICTs in the south and east of the region, this modelling effort should be done as a matter of urgency.

The plans to use tuna to help meet the emerging need for fish for food security in the Pacific (SPC 2008a, Bell et al. 2009) could be more difficult to implement in Melanesia as a result of climate change. These plans include: 1) selling tuna of low export value on local markets to provide fish for the urban poor, and 2) establishing low-cost, inshore fish aggregating devices (FADs) in rural areas to improve access to tuna for subsistence fishers.

Projections that cyclones will become progressively more intense may increase the risk of damage to shore-based facilities and fleets for domestic tuna fishing and processing operations in PICTs located within the cyclone belt. For all PICTs, rising sea level will eventually make many of the existing wharfs and shore-based facilities unusable. Careful planning will be needed to ensure that future investments in this vital infrastructure are ‘climate proof’.

The fact that cyclones are not projected to become more frequent in the southern Pacific means that there should be little effect on the number of days suitable for fishing at sea. However, the dangers associated with more severe cyclones may require some fleets operating or based in subtropical PICTs to be upgraded to sizes that confer acceptable standards of safety at sea under such conditions.

Taken together, the increased costs associated with repairing and relocating shore-based facilities, and addressing increased risks to occupational health and safety for fishermen, will affect the profitability of domestic fishing operations. This will need to be taken into account by PICTs when planning the optimum mix of developing local industries for tuna and providing continued access for DWFNs.

4.2 *Changes to coastal fisheries production*

Significant changes can be expected in the availability and relative abundance of the fish and invertebrates that currently support coastal fisheries in the Pacific. Although there is still little certainty about how changes to water temperatures, acidity of the ocean, current regimes, availability of nutrients and cyclone intensity will affect coastal fish species directly, there is more confidence about how climate-induced changes to their supporting habitats (coral reefs, mangroves, sea grasses and intertidal and shallow bare sediments) will affect these fish and the fisheries they sustain.

The projected effects of climate change on coral reefs are better understood than for other coastal habitats. Rising sea surface temperatures and more acidic oceans are projected to have increasingly severe impacts on the growth of hard corals. In recent decades, mass 'coral bleaching' – expulsion by corals of the symbiotic algae (zooxanthellae) that provide them with energy – has increased in frequency and severity. For many corals, bleaching occurs when sea surface temperatures exceed the normal maxima by 1-2 ^{0}C for 3-4 weeks. Deprived of their energy source, corals slow their growth, have lower reproduction and become much more susceptible to physical damage, being overgrown by algae and infected by diseases. Periods of extended bleaching result in death of corals. The rate of gobal warming is projected to outstrip the capacity of many corals in the Pacific to adapt (Hoegh-Guldberg et al. 2007). This is predicted to result in a net loss of structural complexity on coral reefs because the rate at which corals die and erode following bleaching is likely to exceed the rate at which new corals form.

This situation will be compounded by the acidification of the ocean, which reduces the carbonate available for construction of coral skeletons (Hoegh-Guldberg et al. 2007). As the acidity of the ocean increases, the balance between calcification (reef building) and bioerosion of reefs – excavation of coral skeletons by animals like parrotfish, sea urchins and boring polycheate worms – will be upset, accelerating the collapse of reefs. The growth of some corals in Australia has already begun to slow due to reduced rates of calcification (De'ath et al. 2009). More powerful waves from stronger cyclones will exacerbate the destruction of reefs in PICTs within the cyclone belt.

Taken together, these aspects of climate change are projected to progressively reduce the biological and structural complexity of coral reefs. A rise of 2^{0}C in water temperature and atmospheric concentrations of CO_2 of 450-500 ppm will eliminate most branching corals and reefs will be dominated by macro-algae. If water temperatures increase by >3^{0}C and CO_2 exceeds 550 ppm, reefs are likely to consist mainly of coral rubble (Hoegh-Guldberg et al. 2007). The onset of such degradation is expected to occur even earlier in places where overfishing removes the herbivores which feed on the algae that normally impedes the growth of coral (Hughes et al. 2003, 2007).

The loss of structural and biological complexity on coral reefs will have profound effects on the types of fish and invertebrates associated with them. Species that depend on live coral for food, and on the intricate variety of shelter created by structurally complex reefs for their survival, are likely to disappear (Wilson et al. 2006, Graham et al. 2006, Pratchett et al 2008). These coral-dependant and highly specialist reef fishes may be replaced by herbivorous and generalist species, leading to changes in community structure rather than net losses of biodiversity or productivity (Bellwood et al. 2006). However, this simplification of reef habitats, will involve the loss of many existing energy pathways and make these ecosystems much more sensitive to future disturbances, including overfishing (Nyström et al. 2008). Effects of climate change on coastal fisheries associated with coral reefs may not be immediately apparent, but result in slow, long-term (decadal) declines in yields as resilience and productivity are gradually eroded.

The demise of coral reefs is not the only factor that will affect coastal fisheries resources. Depending on the location of PICTs, projected increases in temperatures, sea level, cyclone intensity and turbidity of coastal waters due to higher rainfall, can be expected to affect the growth and survival of mangroves, seagrasses and non-reefal algal habitats, and the nature of intertidal and subtidal sand and mudflat areas. Although the role that these habitats play in supporting fisheries production in the Pacific is poorly understood compared to that of coral reefs, there is evidence that the vegetated areas provide important nurseries for juveniles (Coles et al. 1992, Bloomfield and Gillanders 2005), and they all provide important feeding habitats for a wide range of coastal fish species (Coles et al. 1992, MacIntyre et al. 1996a, Bloomfield and Gillanders 2005). Reductions in coverage and structural complexity of the vegetated habitats due to more severe disturbance from cyclones, increased stress from higher temperatures, reduced light levels from more turbid conditions and increasing sea levels, can be expected to reduce recruitment success for many species of fish and invertebrates (Lovelock and Ellison 2007, Sheaves et al. 2007, Waycott et al. 2007, Gilman et al. 2008). Erosion of intertidal flats, and changes to the associated microalgae that drive the high productivity of these areas (MacIntyre et al., 1996b), are likely to occur as a result of more intense cyclones and sea level rise. Such changes can be expected to alter the function of intertidal flats as feeding areas for fish.

Given the vital role that coastal fisheries play in subsistence throughout the Pacific (Dalzell et al. 1996, SPC 2007a, 2008a, Bell et al. 2009), one of the greatest impacts that climate change is likely to have is on food security. If future production of fish from coral reefs and the other coastal habitats decreases, or is comprised of fish not readily accepted as food by local communities, the emerging gap in the fish needed for food security will increase. This will place even more pressure on governments to allocate an increasing proportion of their tuna resources for local food security.

The effects of climate change on valuable invertebrate export commodities, such as trochus and sea cucumbers, have yet to be determined. On the one hand, increased acidification of the ocean could affect the survival of trochus by making their shells significantly weaker and increasing their exposure to predators during the vulnerable juvenile stages. Similarly, the growth and survival of sea cucumbers could be impeded by poorer development of their spicules (Kinch et al. 2008). On the other hand, it is possible that the predators of these valuable invertebrates could be reduced, and algal food sources enhanced, by climate change. Any such effects will be difficult to determine in many countries due to chronic overfishing. Management must strive to rebuild viable spawning stocks so that these resources not only deliver more benefits, but are more resilient to adverse conditions and able to take advantage of any favourable changes to their ecosystems.

There is a reasonable risk that the projected changes to coral reefs and the fish and invertebrates associated with them will make it more difficult to supply the diverse range of organisms demanded by the marine ornamental trade (Warbitz et al. 2003.). However, the progressive nature of these changes should enable enterprises to adapt. The industry, which employs hundreds of people in Fiji alone, has proved to be responsive to substantial recent changes in the market place. Therefore, it should be able to capitalize on any opportunities to supply valuable species favoured by climate change, or to culture selected popular species no longer readily available in the wild.

4.3 *Changes to freshwater fisheries production*

The imprecision of the estimates of production and value of freshwater fisheries in the Pacific documented in this volume underscores the need for a more thorough understanding of the benefits of these resources to local economies. Native and introduced freshwater fish and invertebrates may be making greater contributions to fisheries catches than governments appreciate. In particular, freshwater fish and invertebrates may be providing much of the animal protein in large areas of inland Papua New Guinea (PNG). The quantities consumed have yet to be confirmed. The potential importance of freshwater resources is evident in the Sepik River catchment, PNG, where more than 350,000 people live and at least 15 species are caught for food, several of which were introduced for this purpose (Coates 1987; Dudgeon and Smith 2006). A range of freshwater species (e.g., tilapia, *Macrobrachium* prawns and mussels) are also harvested regularly from lakes and rivers elsewhere in the region. Future household income and expenditure surveys in these countries need to be modified to quantify the contribution of freshwater resources to the national diet (Bell et al. 2008).

In PNG, freshwater fisheries resources also contribute to employment. Even in highland areas of Papua New Guinea, where fish stocks are very poor, over 50% of the population engage in fishing activities in many areas, traditionally for eels but more recently catches include a number of exotic species (Coates, 1996). In the Fly River, there are plans to harvest ~5000 tonnes of freshwater herring p.a. to produce fishmeal for aquaculture and animal husbandry.

The freshwater fisheries of PNG are based on a broad range of river channel and floodplain habitats, fed by some of the highest levels of rainfall on earth. The cycles of flooding not only govern the life cycles of the fish in these habitats but also how, where and when people can fish. The projected increases of rainfall in the tropics of 5-15% by 2035, and 10-20% by 2100 (Table A1) are expected to increase the extent and duration of inundation. The effects of increased flooding and higher water temperatures on the fish themselves, and the vegetated lowland areas that support them, have yet to be determined. This must be done quickly so that the species likely to be favoured or disadvantaged by the changing conditions can be determined, and the implications for food security and development of enterprises identified.

Increased flooding and warmer water is also expected to enhance the ability of some exotic species to colonise PNG from Irian Jaya. This has already happened in the case of snakehead. Where the new exotic species are accepted well as food, and do not displace valued indigenous species, this will benefit households. Where undesirable fish invade, communities will need to be given options to derive other benefits from them, e.g., as ingredients for feeds for poultry, pigs and small pond aquaculture.

Freshwater fisheries throughout the region are based largely on species that migrate between the sea and freshwater. The combination of rising sea-level, and changes in rainfall and runoff, are likely to affect habitats and fisheries in both estuarine and freshwater reaches of the region's river systems. Small changes in either rainfall or sea-level may have major impacts on the ability of fish to move between estuaries and freshwater, impacting nursery ground function (Sheaves and Johnston 2008). These effects also need to be evaluated quickly to determine the potential implications for fishery production, food security, and livelihoods.

4.4 *Effects on aquaculture*

The latest SPC Aquaculture Action Plan (SPC 2007b) indicates that small pond aquaculture has potential to provide fish for future food security in the region. Analyses of where such production is likely to be practical and cost-effective, and investments in launching the necessary research and development, will need to be made in the near future if this relatively simple form of aquaculture is to make a significant contribution to food security by 2030.

Tilapia is arguably the easiest species to produce in small ponds, and the introduced freshwater fish species with the broadest appeal in the Pacific. Increasing surface temperatures should enable tilapia to be grown at increasingly higher altitudes in PNG. Provided systems can be developed to distribute fingerlings effectively to remote areas, and suitable feeds based on local ingredients can be formulated, small pond aquaculture has potential to progressively contribute much-needed animal protein in inland PNG and on high islands elsewhere in the region. However, increased levels of rainfall, particularly if it occurs as heavier events, will increase the risks in lowland areas. These risks would include: losing fish from ponds during floods, invasion of ponds by unwanted species and damage to ponds through infilling and breaching of walls. On the other hand, heavier rainfall in low-lying tropical PICTs may increase the area suitable for rain-fed pond aquaculture.

Emerging plans to develop cage culture of fish in coastal waters will need to consider the increased risks to investments in infrastructure due to more severe, albeit less frequent, cyclones in those PICTs within the cyclone belt. In tropical PICTs, the possible beneficial or adverse effects of warmer water temperatures on growth, and the incidence of diseases, will need to be assessed.

The range of aquaculture commodities being developed in the region to support sustainable livelihoods (SPC 2007b), will also be affected by climate change. Preliminary assessments of some of the impacts are summarized below.

Pearl farming faces risks from increased acidification of the ocean. As aragonite saturation levels fall (Table A1), the shells of blacklip pearl oysters will be weaker. This is likely to lead to higher rates of predation of juveniles and lower rates of collection of wild spat. Large-scale farms may be forced to rely more heavily on hatcheries to produce spat, increasing production costs. It also remains to be seen whether acidification will impair the ability of pearl oysters to form nacre. If so, pearl quality may decline progressively, reducing the value of pearls produced in the future. More severe cyclones can be expected to increase the risk of damage to the infrastructure of pearl farms in subtropical PICTs.

The ‘winter syndrome’ disease currently causing problems for the production of blue shrimp in New Caledonia may ease with the changing climate. Increases in water temperatures, and increases in salinity of ponds as a result of the reduced rainfall projected to occur in subtropical areas, could progressively reduce the occurrence of conditions favoured by the pathogen. These are complex zoo-technical issues, however, and it is currently difficult to predict how shrimp pathogens may respond to these projected temperature and salinity increases, not only in winter but also at the height of summer. Warmer temperatures may also extend the duration of the present single-cycle shrimp growing season and allow production of warmer water species, such as *Penaeus monodon*.

Climate change may affect the viability of farming seaweed (*Kappahycus* or “cottonii”) over the longer term. As a general rule, conditions that cause coral bleaching are also bad for *Kappaphycus*. Higher water temperatures combined with lowered salinity are factors linked to outbreaks of Epiphytic Filamentous Algae (EFA) and “ice-ice” disease that reduce production of *Kappaphycus* (Ask 1999). In the more tropical high-island countries, increases in total rainfall will render fewer locations suitable for culture. As coral reefs degrade and herbivorous fish become more prevalent (see Section 4.2), the risk of losses of cuttings and crops to such fish, already a problem at some sites, may increase further.

Warmer water temperatures, increased acidification and more severe cyclones can also be expected to influence the development of aquaculture for marine ornamental products. Village-based farmers in tropical PICTs growing corals and giant clams will face the risk of increased losses due to bleaching, whereas those in subtropical areas will incur greater risks to equipment and loss of stock from rougher sea conditions associated with more intense cyclones. Larger-scale investors able to operate hatcheries in sheltered locations may benefit from market opportunities as sought-after specimens become more scarce in the wild due to degradation of coral reefs. Ultimately, however, the viability of such operations will depend on their capacity to compete with the enterprises culturing ornamentals emerging in Asia.

5. Adaptations to Maintain the Benefits of Fisheries and Aquaculture

In a changing world, both industry and communities will need to adapt past practices to maintain the benefits from fisheries, and to take advantage of new opportunities emerging from altered resources. One of the keys to successful adaptation will be diversification – the more options that industry and communities have to produce, process and distribute fish, the greater the chance that some of them may be favoured, or not affected, by climate change.

To maintain the benefits of skipjack tuna in the face of redistribution of the stock, PICTs in the western Pacific will need to develop ways to add more value to the lower fish catches projected for their EEZs. Adaptations that promote successful domestication of the industry will be important. Displacement of tuna further east will automatically confer more options to the PICTs there. They will need to undertake thorough analyses to identify the most practical and profitable mix of domestication vs access to DWFNs, and the adaptations needed to implement their selected strategies.

For the longline industry, warmer water temperatures and altered ocean currents may change the location of the most profitable fishing grounds, and the composition and abundance of bycatch species. If so, gear and baits may need to be adapted to exclude unwanted, or attract desirable, species.

Ways that coastal fishing communities can diversify their production to continue to catch the quantities of fish they will need for food security include the use of low-cost inshore FADs to provide better access to tuna, and development of small pond aquaculture to supply fish when it is too rough to fish at sea (SPC 2008a, b). However, these simple production methods cannot provide improved access to fish everywhere in the region. Instead, coastal communities may fall into one of seven broad vulnerability categories with respect to their need and potential to adapt in these ways (Table A2).

Table A2. Broad categories of vulnerability of coastal communities to future shortages of fish

Vulnerability rating (increasing)	Coastal fisheries expected to meet future demand	Area suitable for anchored, inshore FADs	Area suitable for pond aquaculture
1 Very low	✓		
2 Very low – low	X	✓ *	✓
3 Low	X	✓ **	✓
4 Low-medium	X	✓ *	X
5 Medium	X	✓ **	X
6 High	X	X	✓
7 Very High	X	X	X

Source: Secretariat of the Pacific Community *FADs anchored in depths < 500 m and within paddling distance by canoe, i.e., within 2 km of the coast; ** Boat and motor needed to reach FADs anchored in depths < 1000 m within 6 km of the coast.

Investments in understanding where and how the vulnerability of coastal communities to shortages of fish can be reduced through diversifying their production will not only help build resilience to climate change, it will also help these communities cope with disasters such as tsunamis. In cases where it will remain difficult to diversify the production of fish, governments will need to place more emphasis on other aspects of the broader livelihood approaches required to build resilience to shortages of food, e.g., development of "climate ready" crops and plant varieties to diversify local agricultural production systems (SPC 2009).

Another key way of adapting coastal fisheries to provide future food security will involve development and uptake of methods to increase the shelf life of tuna when large catches are made around FADs. This will be particularly important in PICTs where the occurrence of tuna is projected to become more sporadic.

The general approach outlined for diversifying production, processing and distribution of fish in coastal areas can also be applied to inland communities dependent on freshwater fisheries. However, their options may be largely limited to development of pond aquaculture in ways that can withstand increased risks of flooding.

Owing to the fledgling status of much of the aquaculture in the Pacific (Bell and Gervis 1999, SPC 2007a), policy makers and planners need to consider not only the impacts of climate change on aquaculture as it is now, but also on how it may evolve in the future. There is much room for flexibility in the way this sector develops. Aquaculture itself promises to be a tool for adaptation to some of the impacts of climate change on fisheries.

6. Gaps in knowledge and priority activities

In preparing this preliminary report, it was evident that there are many gaps in the knowledge required to make sound projections about the likely effects of climate change on fisheries and aquaculture in the Pacific. Investments are needed to fill these gaps so that future assessments can be made with greater confidence. A preliminary list of the key activities that need to be supported is set out below.

- High-quality observations of surface weather for PICTS, and oceanographic conditions in the Pacific. These observations are needed to detect the nature of a changing climate and Pacific Ocean, and the significance of their linkages to the region's ecosystems.
- Down-scaling of climate change and oceanographic modelling to the scales of islands. This will allow more rigorous assessment of local sensitivity and vulnerability of PICTs to a changing climate and ocean.
- Improved modelling of the responses of tuna to climate change, including yellowfin tuna and albacore. Future models should incorporate projected fishing effort and interactions between tuna species. They will also require descriptions and long-term observations of the macrozooplankton and micronekton that provide food for tuna between a depth of 1200 m and the surface to quantify accurately the link between production in the photic zone and tuna abundance.
- Identification of areas likely to be suitable for diversifying coastal and/or freshwater fisheries production through the establishment of low-cost inshore FADs and/or small pond aquaculture.
- Scaling-up regional research facilities to support key experiments and fieldwork on coastal habitats and climate change. Examples of such research include: 1) evaluating whether dissolution of coral reefs due to decreasing pH will be 'capped' at local scales through buffering by the dissolved carbonate; and 2) assessing the effects of rising temperature and pH on coral reef fish and invertebrate species important for food security and aquaculture.
- Inventory of vegetated coastal habitats, including their connectivity to coral reefs, environmental thresholds for growth and survival, and links to fisheries productivity.
- Research and modelling to assess: 1) the habitat and freshwater flow requirements, and connectivity, needed to sustain riverine and estuarine fisheries in PICTs; and 2) projected changes in the area and availability of floodplain habitats for fisheries production, and for pond aquaculture. This will allow better assessment of possible changes in production and species composition of freshwater fisheries resources, and the potential for lowland small pond aquaculture, under climate change.
- Assessment and monitoring of the size and composition of coastal and inland fishery landings across the region to assess changes in catch resulting from climate change, and the success of adaptations to retain the benefits of fisheries.
- Investigations of the risk of increased incidence of pathogens for important aquaculture species, such pearl oysters, shrimp and seaweed, during climate change.

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