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# ENVIRONMENTAL CONSEQUENCES OF OCEAN ACIDIFICATION: A THREAT TO FOOD SECURITY

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***"Save Our Seas- Acid Ocean"*** *- Awareness of the ocean acidification issue is increasing. Following reports on the $CO_2$ rich waters off Alaska in 2008[70], commercial fishermen and other stakeholders recognised the potential impact of ocean acidification and aptly demonstrated their concern. In Homer, Alaska, commercial fishermen and other mariners formed an SOS to raise awareness about ocean acidification caused by fossil fuel emissions.*
*Photo: Lou Dematteis (2009) Associated Press.*

# 1. Introduction

Increased carbon dioxide ($CO_2$) from the burning of fossil fuels and other human activities continues to affect our atmosphere, resulting in global warming and climate change[1]. Less well known is that this carbon dioxide is altering the chemistry of the surface oceans and causing them to become more acidic[2]. From scientists and marine resource managers, to policy and decision-makers, there is growing concern that the process called ocean acidification could have significant consequences on marine organisms which may alter species composition, disrupt marine food webs and ecosystems and potentially damage fishing, tourism and other human activities connected to the seas[3].

Ocean acidification, which affects the carbonate chemistry of the ocean, is directly caused by greater atmospheric emissions of $CO_2$ [4]. These emissions have increased over the last 200 years, primarily due to intensified industrialisation and agriculture resulting in greater burning of fossil fuels, cement manufacturing and land use change[4]. Many organisms depend on the relatively stable balance of carbonate chemistry which has endured for millions of years until the onset of the industrial revolution. Since then there has been a 30% decrease in pH and a 16% decrease in carbonate ion concentrations. Carbonate ions are used by organisms to make shells and reef systems thus it may be more difficult for organisms to do this in the future as carbonate ions decrease further. These organisms are a human food source (e.g. molluscs), provide food for fish (e.g. pteropods are eaten by salmon) and create ecosystems and refuges for fish (e.g. coral reefs). As $CO_2$ emissions continue to rise, ocean acidification is rapidly becoming a critical issue with the potential, if unabated, to affect many species and their ecosystems, pertinently including those associated with human food resources. Ocean acidification is happening now, is measurable and will increase as more $CO_2$ is emitted[5]; it is likely that if $CO_2$ emissions continue at the same rate ocean acidification will have a considerable influence on marine-based diets for billions of people worldwide.

**Ocean Acidification: Simple chemistry - Global impact**

The basic chemistry of sea water is being altered on a scale unseen within fossil records over at least twenty million years[6], and it is happening at an unprecedented rate not experienced in the last 65 million years[7]. The chemistry is straightforward: when $CO_2$ enters seawater it produces a weak acid known as carbonic acid, which is unstable and leads to an increase in hydrogen ions. These ions increase ocean acidity, measured as lower pH, and reduce carbonate ion saturation[3, 8].

The pH scale is logarithmic and measures how acidic or alkaline a substance is; it ranges from 0 - strong acid to 14 - strong base while 7 on the scale indicates neutral. The oceans are naturally alkaline, with a mean surface ocean pH of about 8.2 in 1750. Today surface ocean acidity has increased by 30% (resulting in a drop in mean pH of 0.1 to about 8.1 on the logarithmic pH scale) due to the vast amount of man-made $CO_2$ absorbed by the oceans since pre-industrial times – an estimated 500 Gigatonnes or 25% of that emitted to the atmosphere[4]. If we continue at this rate the ocean pH will decline by a further 0.3 by the end of this century, an unprecedented 150% increase in ocean acidity[2, 3]. This rate of change has not been experienced for around 65 million years, since the dinosaurs became extinct.

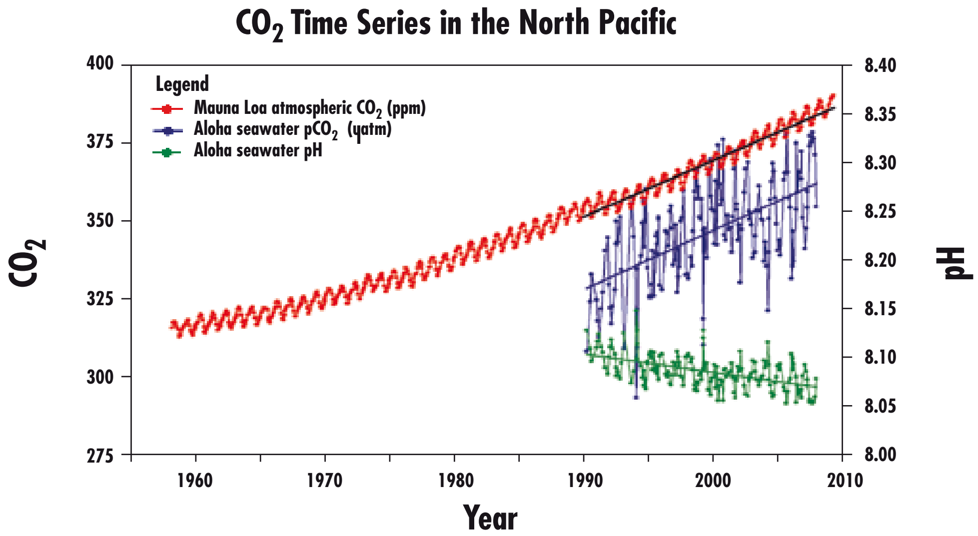
Such a major change in basic ocean chemistry is likely to have substantial implications for ocean life in the future, especially organisms that require calcium carbonate to build shells or skeletons[3, 9-11]. Not all organisms will react at the same rate or in the same way to decreasing carbonate ion concentration[12,13]. There are three naturally occurring forms of calcium carbonate used by marine organisms to build shells, plates or skeletons: calcite, aragonite and high-magnesium calcite. For example, microscopic plants called coccolithophores surround themselves with protective calcite plates; aragonite is used by pteropods to build their shells and corals use it to make their skeletons that help to form reefs; while some echinoderms – starfish, sea urchins, brittle stars - utilise magnesium calcite to form their exoskeletons[3, 10]. Magnesium calcite is more soluble and sensitive to ocean acidification than aragonite; with calcite being the least soluble of the three. A lowering of pH and reduction of carbonate ions will make it more difficult for organisms to sustain their calcified shells, and in undersaturated conditions, waters become corrosive to these minerals.

Additionally, most multicellular marine organisms have evolved a regulatory system to maintain the hydrogen ion balance of their internal fluids[14] and spend energy doing this so an increase in hydrogen ions in seawater means that they will have to divert more energy away from important processes such as growth and reproduction to do this. However, studies of mussels, crab and sea urchin species have shown they have only a partial or no, compensation mechanism[15] potentially making them more vulnerable than those organisms that possess a compensation mechanism.

## 2. $CO_2$, climate change and ocean acidification

Seawater acidity varies across the oceans with temporal changes reflecting seasonal changes in biological activity (Fig. 1) and geographical variations depending on other factors such as seawater temperature and depth[4, 5]. However, ocean observations at a station off Hawaii over the last 20 years show increases in seawater $CO_2$ and decreases in seawater pH clearly tracking increases in atmospheric $CO_2$ (Fig. 1). The global ocean average pH was 8.2 before industrialisation but ocean acidity has risen as the oceans have absorbed increased amounts of $CO_2$ emissions. Consequently, there has been a decrease in pH of 0.1 which, significantly, represents a 30% increase in seawater's acidity[2-4].

**Figure 1:** The Mauna Loa records of atmospheric $CO_2$ over the last 50 years with the surface ocean $CO_2$ and pH recorded off Aloha Station during the last two decades from the Hawaii Ocean Time-Series. Seawater $CO_2$ concentration mirrors the increases in the atmosphere and as seawater $CO_2$ concentration increases pH drops.

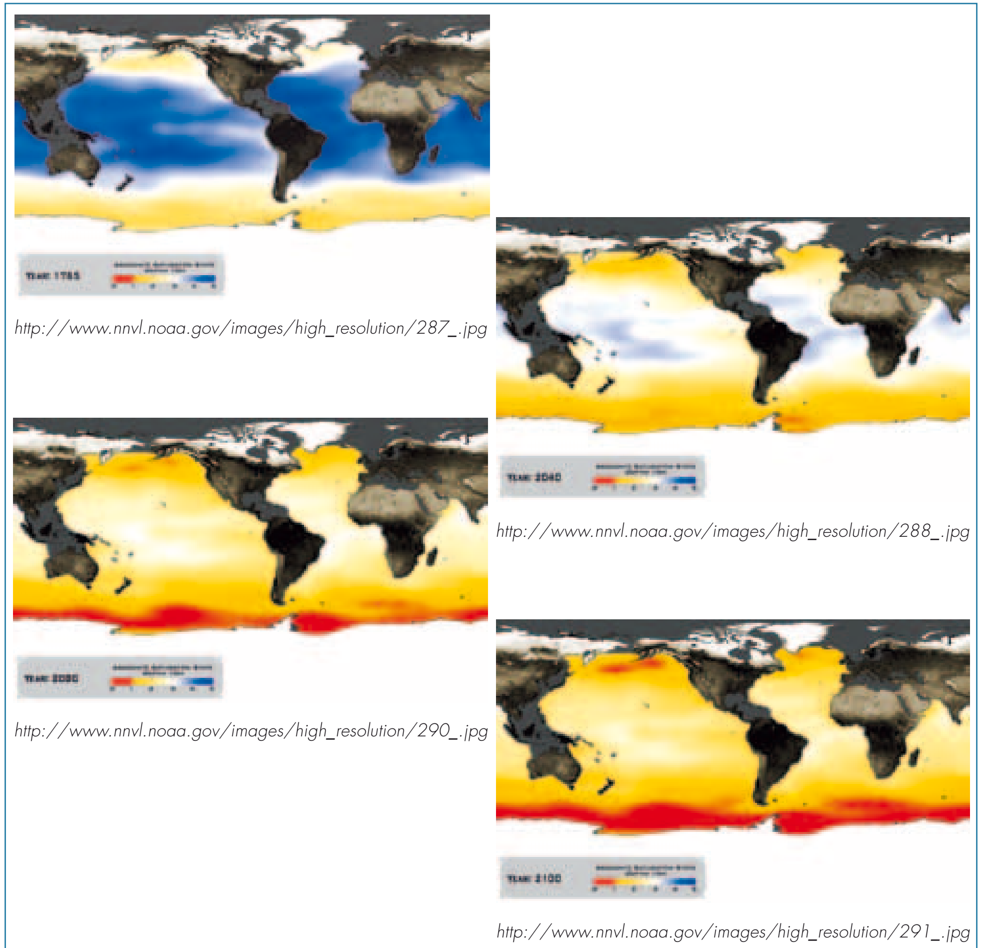



*Source: Feely et al. (2009)[5].*

Estimates[2] of future trends in ocean acidification can be made for different $CO_2$ emission scenarios, such as those published by the IPCC[1]. Based on current rates of $CO_2$ emissions, projections show that by the end of the 21st century, global ocean pH will decrease by a further 0.3 units, which represents a total increase in acidity of 150%[2] (Fig. 2). If ocean pH continues to decrease, this could lead to the loss of some shell or skeleton forming organisms[3, 9-11]. Eventually, the sediments in the oceans will buffer these chemical changes but chemical recovery from such events may take tens of thousands of years[16] while a return to the biological status quo, even if possible, could take millions of years[17].

However, organisms are already being subjected to higher levels of $CO_2$ and therefore lowered pH and increased acidity (Fig. 1)[2-5]. If these changes to ocean chemistry continue into the future they may affect the abundance, health, physiology, biochemical properties and behaviour of marine organisms, as adults and/or in their juvenile form[11, 18]. The key question regarding future food security is how ocean acidification will directly affect marine organisms consumed by humans or indirectly via the ecosystems that support them.

**Figure 2:** Model output showing the impact of ocean acidification on the ocean's carbonate saturation state (here showing aragonite saturation) in 1765, 2040, 2080, and 2100. The availability of calcium carbonate is predicted to decrease over the next century. Areas that are deep red are sufficiently acidic to dissolve unprotected calcium carbonate-based shells and skeletons. Most areas currently have enough calcium carbonate to support corals and other organisms, but all areas are predicted to decline by the year 2100 compared to pre-industrial values. The Arctic Ocean is not included in this model but other models focussing on the Arctic project that aragonite undersaturation will occur within decades even before the Southern Ocean[73].

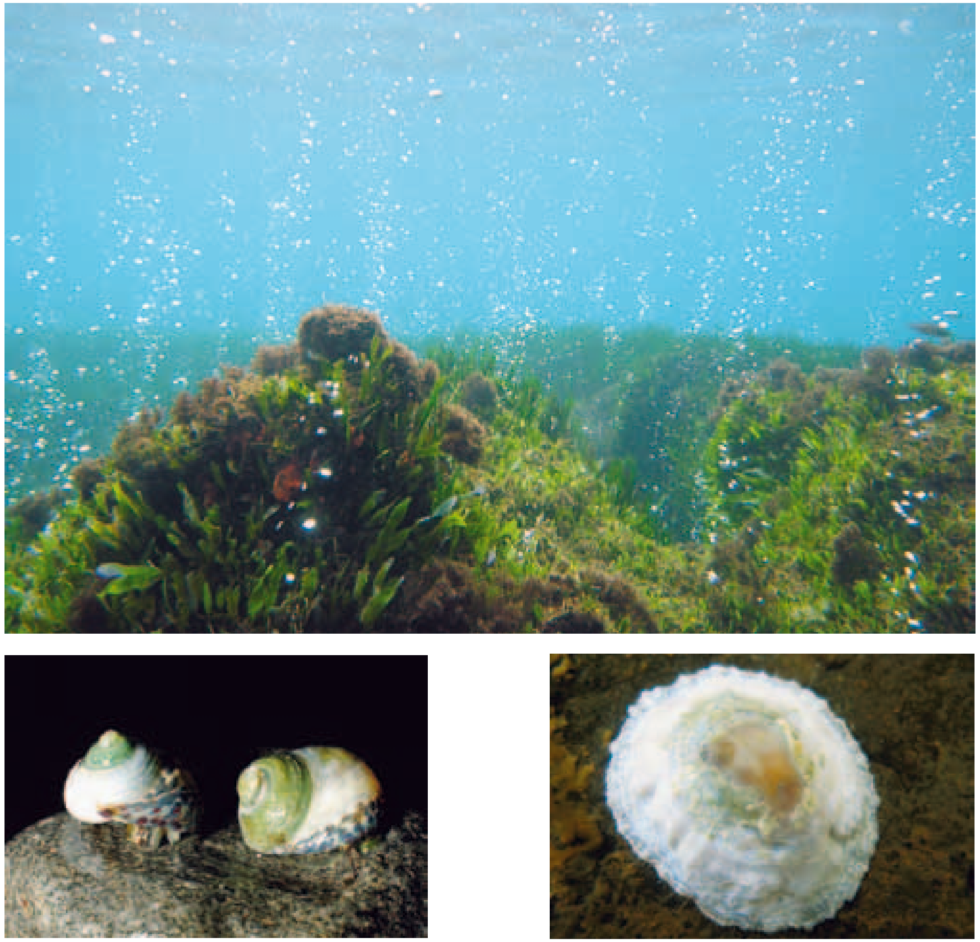



*Source: Model courtesy of NOAA Environment Visualization Laboratory. Amended from Orr et al. (2005)* [9].

**$CO_2$ vents – an insight into how biology may react in a future high $CO_2$ ocean**

In some areas of the world, volcanic vents are pouring almost pure $CO_2$ into the marine environment, so acting as 'windows' on how biology may react to a future 'high $CO_2$ ocean' (Fig. 3). Recent studies of a Mediterranean vent in shallow waters revealed key ecosystem changes in high $CO_2$ areas compared to normal $CO_2$ areas[19]. Certain algae and seagrasses were found to grow more efficiently closer to the vents where there was also a large reduction in biodiversity, notably a loss of calcifying organisms adjacent to the vents where the pH was lowest. Sea urchins were found to be the most sensitive to these changes.

**Figure 3.** Natural $CO_2$ vents from Ischia in the Mediterranean showing productive seagrass beds (top) but shells of calcifying organisms are pitted and corroded (below) due to the increased acidification of these waters.



*Source: Hall-Spencer et al. (2008) Nature* [19].

### A significant combination of ocean stressors

Ocean acidification is occurring alongside other climate-related stressors, such as ocean warming, sea-level rise, and, possibly, changes to precipitation and increased storminess[1]. These are compounded by other non-climate related impacts, including over-fishing and pollution, which add pressure to already strained marine ecosystems that provide food for human consumption[20]. The combination of rising temperature and increasing acidity on organisms is likely to be worse than either on its own, for example, the range of temperature tolerance for the edible crab may be reduced in more acidic waters[21].

## 3. Marine food resources and ocean acidification

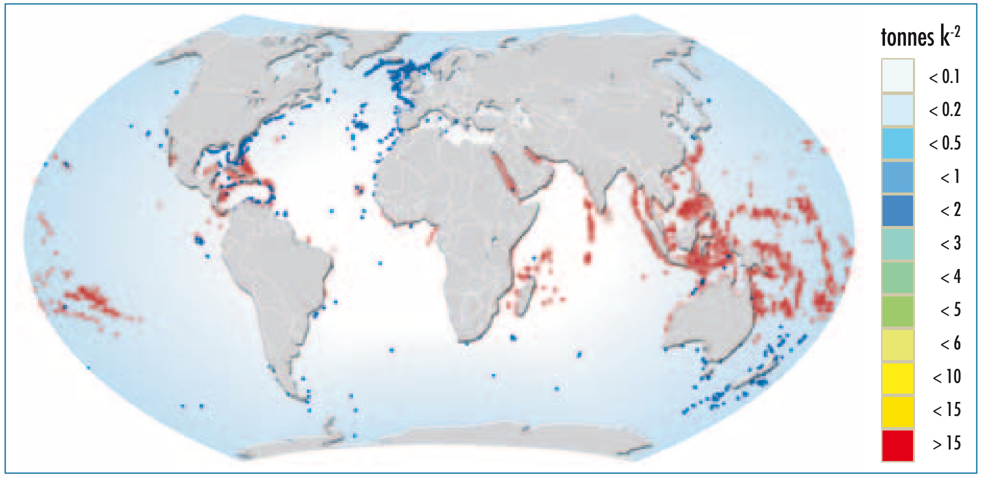
### The significance of the marine environment as a food source

The contribution of marine protein to global food security is substantial. Fish, including shellfish, contribute 15% of animal protein for three billion people worldwide[22]. A further one billion people rely on fisheries for their primary source of protein. Fish are even more important in countries where other protein sources decline seasonally[23].

Primary production forms the basis of the marine food web and is of great importance to maintaining fish stocks. Production is highest in areas rich in nutrients, such as upwelling zones and continental shelf areas. Globally approximately 80% of fish catch are from such areas (Figure 4).

Productivity 'hotspots' such as upwelling regions where cold water is rich in both nutrients and $CO_2$, coastal seas, fronts, estuaries and sub-polar regions often supply the main protein source for coastal communities. However, many of these areas are also projected to be very vulnerable to ocean acidification this century[24, 25]. As world populations rise alongside a predicted growth in coastal populations due to internal migration, the demand for ocean protein products is also likely to rise[23, 26]. Fish stocks, already declining in many areas due to over-fishing and habitat destruction[20, 22, 27], now face the new threats posed by ocean acidification[28].

**Figure 4:** The world's most productive fishing grounds are confined to major hotspots, less than 10% of the World oceans. The map shows annual catch (in tonnes per km²) for the World's oceans. There is a strong geographic concurrence of continental shelves, upwelling and primary productivity and the amount of fish caught by fisheries. The map shows global fisheries landing annual average for the period 2001 to 2006 (updated August 2010).




*Data source: Sea Around Us project, (University of British Columbia, http://www.seaaroundus.org). Map designed by Dr. Reg Watson (http://ecomarres.com). Used with permission.*

It may therefore be no surprise that the aquaculture industry is the fastest growing food producer worldwide, increasing at a rate of 7% per annum, and is widely touted as the panacea for dwindling fisheries. The proportion of fish produced by aquaculture and consumed by humans worldwide rose to 50% of total production in 2009[29].

> **Food Security**
>
> "Food security is a condition when all people, at all times , have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active healthy life"[30].

In local communities, the smaller fish species are often exploited because they are usually the most numerous and accessible[22, 23, 27]. Frequently eaten whole, they also provide other dietary requirements, such as essential oils, minerals and trace elements. Fish are not only the single most important source of protein for some subsistence communities; they also may provide a small income stream that enables the purchase of other staple foods like rice.

However, as small fish occur in large numbers they are also targeted by industrial fisheries to manufacture fish oil and meal for use as a food stock, for example in aquaculture, where fish are used to feed fish[29]. Fish such as trout, tilapia and salmon, and an increasing number of marine species rely on this fish meal, thus placing local resources under an accumulation of pressures.

Invertebrates such as mussels, lobsters and shrimp may be regarded as niche luxury foods but also provide significant income for many poor coastal peoples. As shell growth and physiology are sensitive to increases in ocean acidity, the production and quality of many of these invertebrate species is at risk; they are the most vulnerable group in the aquaculture sector. Some cultured invertebrates also rely on those same small fish used to feed cultured finfish, as well as local human populations, so adding to the accumulation of pressures facing these limited but important fish resources.

Wild fisheries, shellfisheries and aquaculture are therefore of great importance to current and future food security[27]. However, these industries are now also at risk from future ocean acidification both directly through the impact on the organisms themselves and indirectly through the food webs and habitats they depend on.

## Threats of ocean acidification

Although studies about the effects of ocean acidification on marine resources are comparatively new, early results indicate there is no room for complacency. The effect of increased acidity on adult finfish seems minimal in the species investigated[14]. However, their orientation and balance mechanisms as well as behaviour may be sensitive to ocean acidification[31, 32, 74]. The effects on finfish larval and egg stages are not yet understood. However, valuable breeding and feeding habitats are at risk. For example, coral reefs, which underpin many marine fisheries in the tropics, are already under pressure due to destructive fisheries practices, land based pollution and sediment loading, heat stress and coral bleaching[33]. These delicate ecosystems are especially prone to the effects of ocean acidification[34, 35].

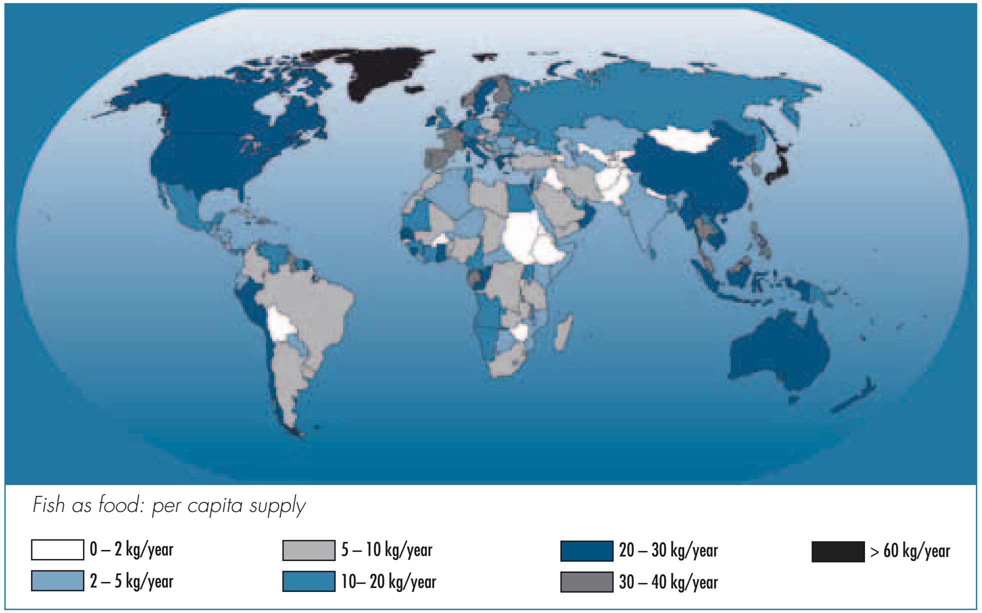
Certain habitats and species of sea grass might 'benefit' from increased seawater $CO_2$; however many animals that rely on these for food and shelter may be negatively affected[19]. The impact of ocean acidification on ecosystems, with the possible exception of coral reefs, is largely unknown. The ability of many planktonic organisms to build skeletons decreases as seawater becomes more acidic but the response is not uniform[12, 36]. Marine ecosystem responses are speculative due to their complexity. However, polar and sub-polar marine ecosystems are projected to become so low in carbonate ions within this century (Fig. 1) that waters may become corrosive to unprotected shells and skeletons of organisms currently inhabiting these waters[9, 73]. Also changes in reproduction, larval development, growth efficiency, behaviour and competition may affect the number and kinds of species in existence, while all of these factors could potentially affect food chains.

### *a. Fishery threats*

Finfish make up the majority of the global catch (over 80%) and are the most significant source of marine protein for human consumption (Figure 5). Most finfish are carnivorous and so depend on the healthy functioning of complex marine food chains. Direct effects on swimming performance of adult finfish such as cod are unlikely due to their inbuilt ability to regulate their internal pH[75]. However, in young clownfish there may be orientation problems due to variable otolith growth rates[31] and altered behaviour towards their predators through impacting their olfactory cues which may increase mortality and impact replenishment of fish populations[32, 74].

The indirect effects of changes in their prey, and loss or damage to their habitats are currently considered more significant than direct impacts. For example, shelled pteropods produce aragonite shells, and observations and controlled experiments show that they will be particularly sensitive to ocean acidification[9, 37]. Pteropods often occur in high densities and form a major dietary component for higher predators such as herring, salmon, whales and seabirds[9].

**Figure 5:** Average per capita fish supply 2003-2005 (in live weight equivalent)




*Source: The State of World Fisheries and Aquaculture, 2008, World Fisheries (FAO22).*

Ocean acidification has also been tentatively linked to increased jellyfish numbers[38] and changes in fish abundance. Jellyfish are key predators in many of the world's pelagic systems; they can affect the abundance of zooplankton, fish larvae and eggs, which affects the survival to the adult stage (or recruitment) of fish populations[39]. As jellyfish are rarely the preferred food for other marine animals[40], any significant increase in their numbers could have major consequences for pelagic ecosystems and fisheries.

Furthermore whilst echinoderms such as sea urchins, starfish, brittle-stars and sea cucumbers are locally significant as a food source, globally they make up only a small percentage of overall catch. However, these species are a critical link in fish food chains; the majority of those studied show great vulnerability in adult, juvenile and egg stages to future levels of ocean acidification[41-45].

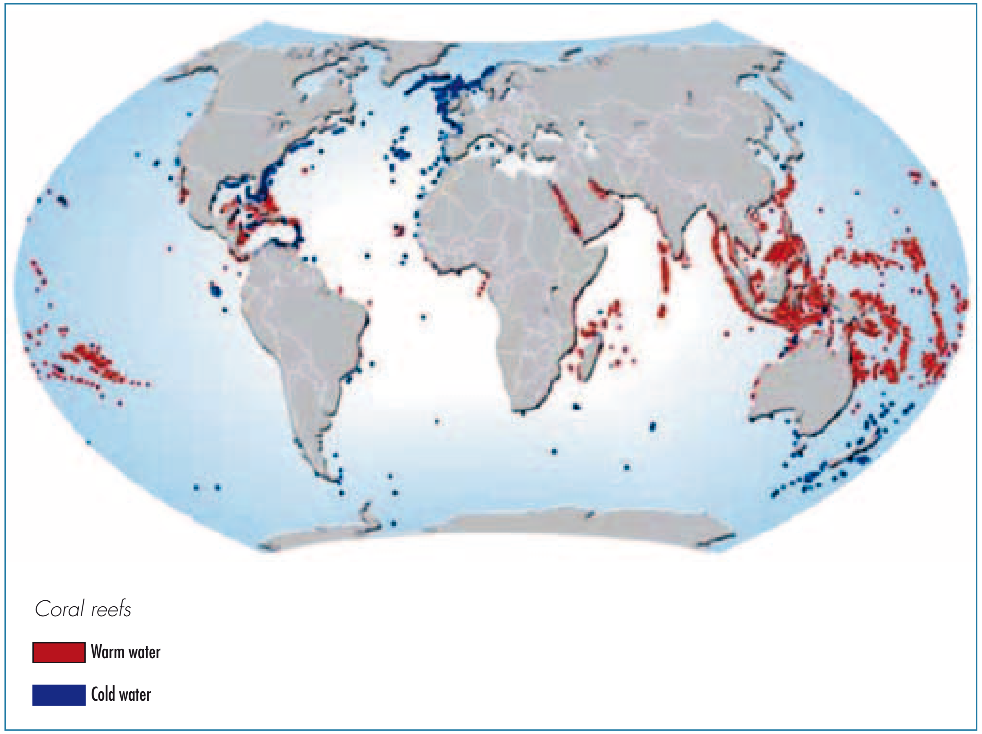
### *b. Coral reef threats*

Corals form the most biologically diverse marine ecosystems and grow from the tropics and mid-latitude to even high latitude cold waters (Fig 6). Tropical reefs provide shelter and food for an estimated 25% of known marine fish species, and account for between 9-12% of world fish landings. Consequently, these coral reefs provide food and livelihood security for some 500 million people worldwide. Significant reef loss would, therefore, impact marine biodiversity, threaten the survival of coastal communities through reduced food sources and reduce the capacity of nearby coastlines to buffer the impact of sea level rise, including increased storm surges[33].

It is anticipated that future ocean acidification will affect adult and juvenile coral growth and recruitment[46], coralline red algae growth[47], reef structural integrity[48] and potentially even the density of bio-eroding grazers and predators[34].

*Scleractinian corals and algal assemblage, including coralline algae. Growth and skeletal integrity of scleractinian corals and coralline algae are likely to be compromised by ocean acidification. Source: Audrey Ringler / UNEP*

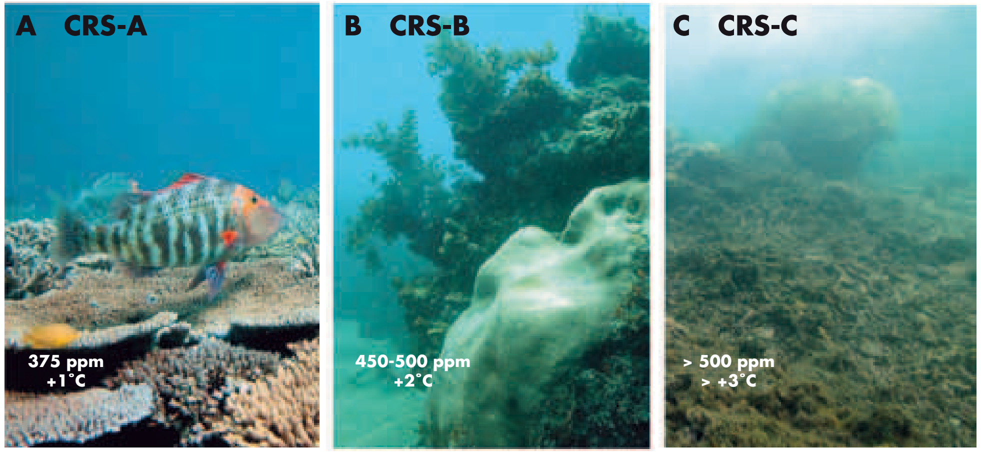
**Figure 6.** Distribution of coldwater and tropical coral reefs. The coldwater reefs are highly susceptible to ocean acidification, which has its greatest impacts at high latitudes. Tropical reefs will become severely damaged by rising sea temperatures.




*Data source: UNEP World Conservation Monitoring Centre, 2005. Map by Hugo Ahlenius, UNEP/GRID-Arendal. http://maps.grida.no/go/graphic/distribution-of-coldwater-and-tropical-coral-reefs.*

This challenge to coral reefs is in addition to the threat of increasing sea surface temperatures, a major cause of coral bleaching[34]. The combined impact of ocean warming and acidification as well as over-fishing and pollution increases the stress on coral reef ecosystems. Researchers estimate that a $CO_2$ stabilization scenario of less than 450 ppm is essential for the survival of many coral reefs[34, 35], and more reefs will decline (Fig 7) if $CO_2$ concentration exceeds this limit[49].

**Figure 7.** Examples of reefs from Australia's Great Barrier Reef which are used as proxies to indicate what future coral reefs may look like in a high $CO_2$ world under different $CO_2$ scenarios. The atmospheric $CO_2$ and temperature increases shown relate to the scenario, not the locations photographed. (A) Reef slope communities at Heron Island; (B) Mixed algal and coral communities associated with inshore reefs around St. Bees Island near Mackay; (C) Inshore reef slope around the Low Isles near Port Douglas.




*Source: Hoegh-Guldberg et al. (2007) Science[34].*

Even cold water corals which generally live in deeper and colder waters (Fig. 6) are important feeding and nursery grounds for finfish and like their tropical cousins are vulnerable to ocean acidification[50-52].

### c. *Threat to aquaculture*

Marine invertebrates like molluscs and crustaceans (Fig 8), increasingly used in aquaculture, show negative responses to acidification at various life stages. An organism's success depends on more than just the growth of its adult form. The life cycle of invertebrates from egg fertilization and development, to growth and timing of different juvenile larvae stages to their settlement, are critical to their own survival as well as that of both their prey and predators[11]. As most shellfish eggs and larvae are planktonic, these species are prone to the negative effects of ocean acidification. One study on the early development of the oyster (*Crassostrea gigas*) shows that shell calcification is reduced in juveniles; their body shape and size are altered, which suggests serious consequences for their survival into adulthood[53].

**Figure 8:** Some invertebrate food species that have shown sensitivity as adults or in other parts of their life cycles to ocean acidification.

*Top left: Mussels beds (Rob Ellis/PML), Top right: Oyster tables (Steve Widdicombe/PML), Mid left: Lobster (Kelly-Marie Davidson/PML), Mid right: Spiny lobster (Kelvin Boot/PML), Bottom left: Sea urchin (Kelvin Boot/PML) and Bottom right: Edible crab (Kelvin Boot/PML).*

Molluscs account for 8% of the global marine catch, but are increasingly important in the growing aquaculture industry. Clams, scallops, mussels, oysters, abalone and conchs provide direct protein sources for various island and coastal communities and are valuable commercial fisheries. As well as providing food some species play an important role in forming and maintaining habitats for other species (e.g. mussel beds, Fig 8). Many mollusc species at the adult and juvenile stages have shown reduced growth and/or health under projected ocean acidification scenarios[53-63].

Crustaceans such as prawns, lobsters and crabs currently comprise 7% of global seafood consumption through both wild and aquaculture species. They are significant locally for subsistence fishing and at larger commercial scales. Studies on the effects of ocean acidification have only been conducted on a few crustacean species[13, 64-68]. However, some of these studies show their vulnerability to elevated seawater $CO_2$ as adults and juveniles while another shows that the ability to tolerate a range of temperatures is reduced[66].

# 4. Conclusion

There are numerous reasons to be concerned about ocean acidification and its future impact at the species and ecosystem level. If ocean acidification continues disruptions to food chains and direct and indirect impacts on numerous species are considered likely with consequent risk to food security.

Habitat destruction, overfishing, climate change and pollution are significantly impacting fishery products and food security and national economies[69-71] and mitigation of these impacts requires coordinated action at the highest levels. Ocean acidification acts in addition to these stressors[28]. All marine environment stakeholders and the policy makers responsible for environmental or food security issues need to become more aware of the potential effects and consequences of ocean acidification[72].

### Emerging challenges and their implications

There is a need to more fully understand the effects of ocean acidification on various marine organisms at different stages of the lifecycle including the ecosystem level impacts. Critical species within ecosystems or food chains that act as food sources should be a priority for research. Impacts from ocean acidification must be understood within the wider context of other real and potential threats such as from climate change and pollution as well as global trends in world fisheries and aquaculture[69-71]. The obvious solution to the potential threats posed by ocean acidification is to make rapid and substantial cuts to anthropogenic $CO_2$ emissions to the atmosphere and hence, oceanic $CO_2$ concentrations. However, the likelihood is that this will not occur in the immediate future. Ocean acidification is a rapidly emerging issue with many nations starting to invest in research into the potential future impacts on organisms, ecosystems and food providing products in earnest[72]. So, based on existing information, which may change as new data emerges, the following actions are judged necessary to mitigate the risk of effects of ocean acidification:

- Recognize the security, economic and cultural importance of those marine species and habitats that are currently exploited.
- Determine the vulnerability of fish-dependent human communities in terms of exposure, sensitivity and the capacity to adapt to changes resulting from ocean acidification.
- Identify species that are more flexible to change and which may encroach on habitats and survive in altered conditions and assess how these may affect ecosystems and food security.
- Reduce other pressures on food fish stocks to provide the best chances of success through, for example, marine spatial planning or re-evaluating available resources and their usage.
- Assess the options for development of environmentally sustainable 'aquaculture' options using species that are resistant to lowered pH or can be kept in conditions of controlled pH.
- Consider the positive and negative impacts of a chain of substitute habitats such as artificial reefs to provide the diversity of niches that are found in existing habitats.
- Embrace the science and ramifications of ocean acidification and climate change into fisheries management tools.
- Alongside efforts to further investigate the effects and consequences of ocean acidification, foster increased awareness of this issue through diverse media.

### Further Reading

Ocean Acidification Reference User Group (2009). Ocean Acidification: The Facts. A special introductory guide for policy advisers and decision makers. Laffoley, D. d'A., and Baxter, J.M. (eds). European Project on Ocean Acidification (EPOCA). 12pp.

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