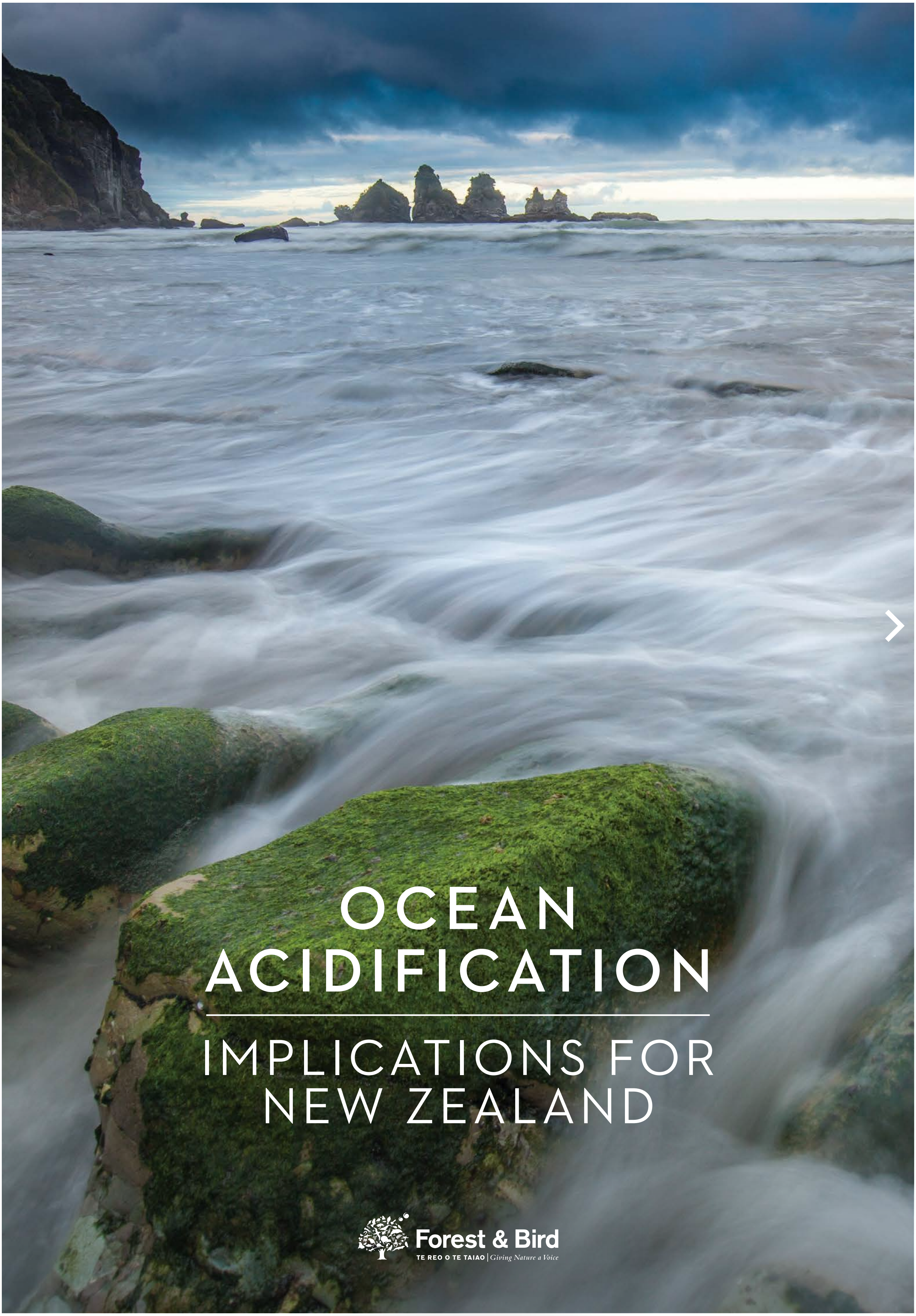


OCEAN ACIDIFICATION

IMPLICATIONS FOR NEW ZEALAND

Forest & Bird
TE REO O TE TAIAO | *Giving Nature a Voice*

CONTENTS

THE OCEANS PLAY A CRUCIAL ROLE IN MAKING THE EARTH HABITABLE FOR HUMAN BEINGS AND OTHER LIVING THINGS.

THEY ABSORB 93% OF THE HEAT IN THE ATMOSPHERE AND ABOUT A THIRD OF ALL THE CO2 EMITTED FROM BURNING FOSSIL FUELS.

Cover photo: Paparoa National Park. © Colin Monteath / Hedgehog House. Photo: © Darryl Torckler.

Our oceans absorb

93%

OF HEAT IN THE ATMOSPHERE

33%

OF CARBON DIOXIDE (CO_2)

WORLDWIDE THE OCEANS ABSORB 93% OF THE HEAT IN THE ATMOSPHERE AND ABOUT A THIRD OF ALL THE CARBON DIOXIDE (CO_2) EMITTED FROM BURNING FOSSIL FUELS.

FOREWORD

As the scale of climate change and the urgent need for action becomes more apparent every day, climate change gains a bigger profile. But it is not the only harmful consequence of burning fossil fuels. Fossil fuel emissions are changing the chemistry of the ocean, threatening key species and the marine food web.

This change in ocean chemistry – ocean acidification – threatens the marine environment, putting at risk marine life we love for its own sake or as a source of food and employment.

Even plankton, the "grass" of the oceans that feeds marine life, is at risk, as is the extent to which oceans can absorb more carbon from the atmosphere than they release back into the air.

Forest & Bird commissioned this report because we are deeply concerned about the danger ocean acidification presents. We want the risks to have a higher profile in the thinking of decision-makers, seafood industry leaders, seafood workers, and the wider public. These risks are magnified by the impact of acidification combined with ocean warming – also caused by rising carbon dioxide (CO_2) emissions – and other human impacts such as pollution and destructive fishing practices.

This report has a broad set of recommendations for parliamentarians, the Government, and industry, and I look forward to engaging with them on these.

Recommendations in the report include amendments to climate and resource management law to acknowledge the role of ocean acidification, increased research into impacts and how to deal with them, and regional action to action to mitigate and adapt to acidification, such as restoring mangroves.

Ultimately, our biggest challenge is to cut CO_2 emissions so that ocean acidification is halted before the damage to our marine environment becomes irreparable.

Kevin Hague
Chief Executive | Kaiwhakahaere Matua,
Forest & Bird | Te reo o te taiao

Forest & Bird would like to thank Alison Maloney for her support of this Ocean Acidification report. Alison was a Forest & Bird member since 2004 who sadly passed away in 2018. After reading an article about Ocean Acidification in the Forest & Bird magazine, she donated money for this report to be completed.

Thank you

INTRODUCTION

Ocean acidification has been called "the other CO_2 problem", but it has started to gain international attention as a major issue only in the past decade or so. Even now public awareness is relatively low, although the oceans and coastal waters play a critical role for all life on our planet.

The truth is that, when it comes to human-induced climate change, you cannot separate the oceans – which cover about 70% of the Earth's surface – from the land. The oceans play a crucial role in making the Earth habitable for human beings and other living things. They absorb 93% of the heat in the atmosphere and about a third of all the CO_2 emitted from burning fossil fuels.

The plants and plant-like organisms of the ocean, from single-cell phytoplankton to seaweeds and sea grasses, create at least half the world's oxygen – as much as all the forests, grasslands, and other vegetation on land. About 17% of the animal protein humans consume worldwide comes from the sea.

Rapid changes in ocean chemistry from man-made CO_2 emissions are potentially unparalleled in the past 300 million years. Already, the oceans are more than a quarter more acidic than they were before the industrial revolution. If we carry on burning more fossil fuels every year, the acidity of our seas will more than double by the end of this century.

We are only just starting to learn what the consequences of such a reckless course of action could be. We know that shellfish, coral, and other calcifying species are likely to be threatened by increased acidity, but many other species may also struggle to adapt. We don't know how acidification will affect the complex food chains and ecosystems of the oceans.

Acidification is not the only threat facing the oceans. There will also likely be far-reaching impacts from ocean warming, such as changes to the distribution of different species, oxygen depletion in some areas, and changes to nutrient availability.

All this is of vital importance to New Zealand. We have rich and diverse marine environments, and important fishing and aquaculture industries. Our culture and many forms of recreation are also tied to the sea.

Although New Zealand's marine environment dwarfs the land mass, there are enormous gaps in our knowledge of what exists in that environment and how marine ecosystems work. In this report, Forest & Bird aims to explain what we know about ocean acidification and associated changes related to rising greenhouse gas emissions in our marine environment and some of the risks we are facing.

Forest & Bird hopes this report will underline the importance of gaining a better understanding of what is happening and of future risks to the seas that surround us as a result of ocean acidification. We also hope it will further underline the crucial importance of acting urgently to reverse the growth in greenhouse gas emissions to safeguard the future for nature and for New Zealanders.

EXECUTIVE SUMMARY

Since the industrial revolution started in the mid-18th century, the burning of fossil fuels and deforestation have caused levels of CO_2 in the atmosphere to rise from about 285 parts per million to more than 400. As CO_2 concentrations in the atmosphere have grown to levels never before seen in human history, the quantity absorbed by the world's oceans has also risen.

Oceans have absorbed about a third of all the CO_2 released into the atmosphere by human activities. This has changed their chemical balance in a process known as ocean acidification. The average pH, which measures the acidity or alkalinity of a solution, of the oceans has fallen from 8.2 units to 8.1 since pre-industrial times. Because pH is measured on a logarithmic scale, like earthquakes, this represents an increase in acidity of 26%.

If greenhouse gas emissions continue to rise in a "business as usual" scenario, the average pH level of New Zealand waters is projected to fall to 7.77 by the end of this century, a 116% increase in acidity since pre-industrial times. This would be the fastest rate of change for millions of years.

Associated with the fall in pH is a decline in calcium carbonate availability in the oceans. This is expected to affect the ability of shellfish, corals, and other calcifying organisms to form and maintain their shells and carbonate structures.

Parts of the ocean – including most of our neighbouring Southern Ocean – are projected to be undersaturated in aragonite, the more soluble form of carbonate, by the end of this century.

In undersaturated conditions, the unprotected aragonite shells and skeletons of corals and some molluscs can start to dissolve.

Studies have also shown that acidification disrupts the sensory system of some fish species and that they change their behaviour in response. Some tropical species lose their wariness of predators and awareness of their surroundings when exposed to pH levels expected in the future. A small number of studies of temperate climate fish have shown similar sensory disruption and lower survival rates for larvae, although research in this area is at an early stage. Acidification is not the only disruption related to climate change occurring in the oceans and coastal waters. Rising sea temperatures will also likely have a profound impact, and already some fish and plankton species have been recorded as shifting towards the poles.

Other warming impacts will include an expansion of low oxygen waters and changes to nutrient availability, currents, and weather patterns. Taken together with the impacts of acidification, these are expected to have far-reaching consequences for ecosystem communities and food webs, from phytoplankton at the base of the food chain to predators, such as marine mammals, sharks, and seabirds.

The world's oceans and coastal waters are already changing because of rising CO_2 levels, and some degree of further acidification and warming is inevitable because of the levels of CO_2 and heat already in the oceans and atmosphere. But those changes will be far more far-reaching and potentially devastating if we allow CO_2 emissions to continue rising through this century. Meeting the commitments of the Climate Change Response (Zero Carbon) Amendment Bill is the single most important thing we can do as a nation.

RECOMMENDATIONS

New Zealanders should take action at all levels to reduce the risks from ocean acidification. We all have a role in cutting CO_2 emissions. Central government, local government, marine industries, and Parliament all have a role to play. This report's recommendations are:

TO THE MINISTER FOR CLIMATE CHANGE

Ensure rapid reduction of CO_2 emissions consistent with a fair contribution towards achieving atmospheric levels of 450ppm of CO_2.

TO PARLIAMENT

Amend the Climate Change Response (Zero Carbon) Amendment Bill to include ocean acidification in all governmental risk assessment and planning for climate change-related adaptation.

TO THE MINISTER FOR THE ENVIRONMENT

Reform the Resource Management Act to include safeguarding the climate and minimising ocean acidification as matters of national importance and to ensure that the CO_2 emissions of an activity are expressly required to be taken into account in decision-making about resource management.

Prepare a national policy statement on climate change that addresses ocean acidification and that includes policies on CO_2 emissions, other activities that contribute to ocean acidification, activities that reduce carbon sequestration, activities that exacerbate ocean acidification (such as mangrove clearance), and activities that promote resilience in the face of unavoidable acidification.

Reform the Exclusive Economic Zone Act to allow for direct and indirect CO_2 emissions to be taken into account when assessing an activity.

TO THE MINISTER OF FISHERIES

Reform the Fisheries Act to adopt ecosystem-based fisheries management that takes into account the risks posed by ocean acidification.

Amend the information principles in the Fisheries Act so that uncertainties about the effects of ocean acidification are not used as a reason to delay action when setting Total Allowable Catches and Total Allowable Commercial Catches.

Support new Marine Protected Areas legislation that has a clear goal of fully protecting (no take) 30% of each bioregion within New Zealand's territorial sea and New Zealand's Exclusive Economic Zone in a meaningful and representative way that builds ocean resilience.

Photo: Cape Reinga, New Zealand. © Mathew Waters, Unsplash.

TO THE MINISTER OF CONSERVATION

Adopt new Marine Protected Areas legislation that has a clear goal of fully protecting (no take) 30% of each bioregion within New Zealand's territorial sea and Exclusive Economic Zone in a meaningful and representative way that builds ocean resilience.

Advocate for and protect biodiversity that helps mitigate the impacts of ocean acidification, such as coastal mangrove and kelp forests, coastal wetlands, and seagrass beds.

TO THE MINISTER OF RESEARCH, SCIENCE AND INNOVATION

Fund a comprehensive programme of research into the likely impacts and implications of acidification and warming, and ways of addressing those impacts.

Fund research into the risks to New Zealand native migratory fish species from ocean acidification.

TO REGIONAL COUNCILS AND TERRITORIAL AUTHORITIES

Ensure that regional policies and plans established under the Resource Management Act mitigate the effects of acidification, including by preventing the removal of mangroves and by reducing run-off, sewage, and other contaminants into coastal waters.

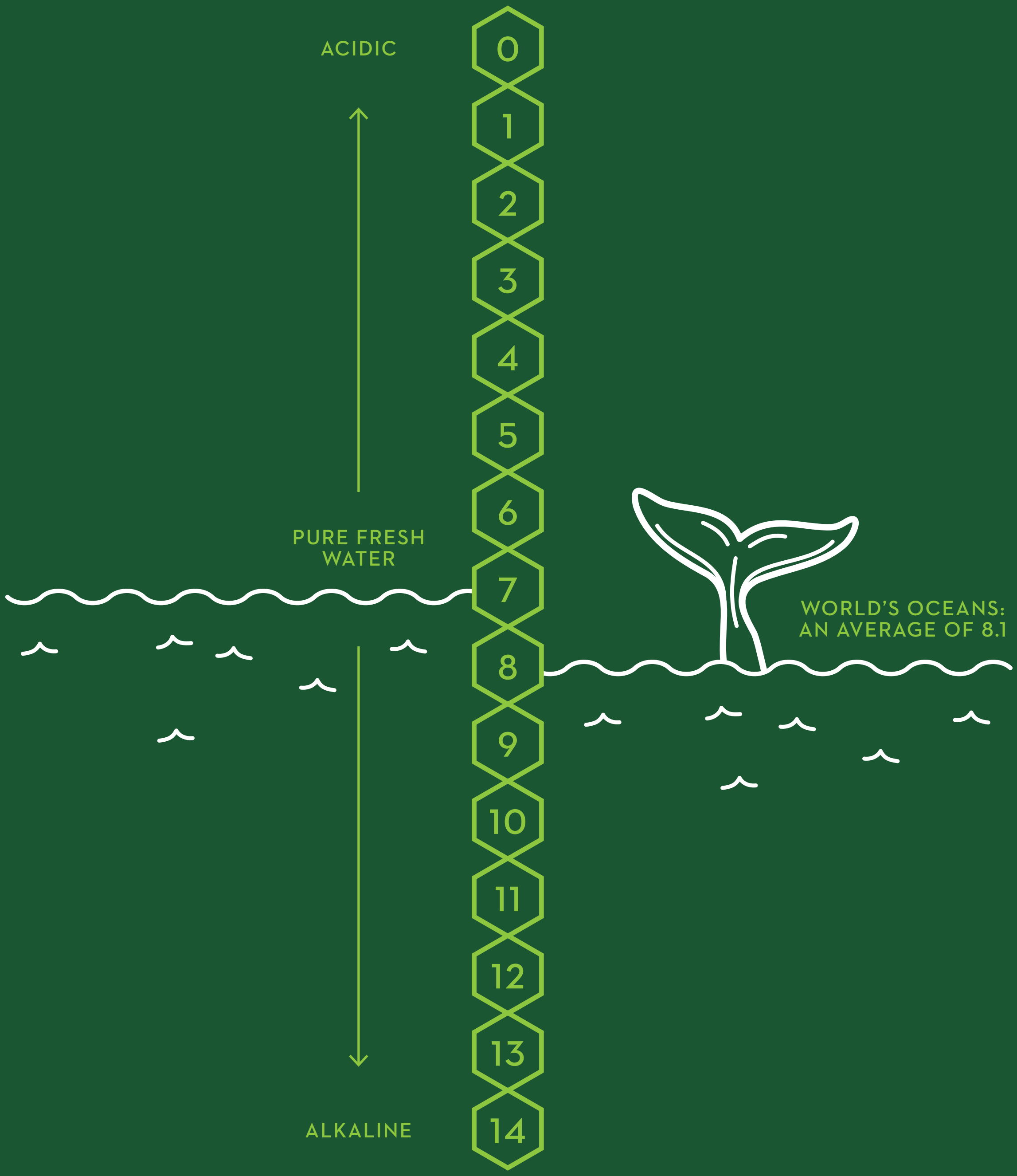
TO MARINE FISHING AND FARMING INDUSTRIES, AND TO UNIONS REPRESENTING WORKERS IN THESE INDUSTRIES

Advocate for rapid and substantial cuts in global CO_2 emissions to reduce risks to marine fishing and farming industries from ocean acidification.

Strongly advocate for domestic legislation that rapidly reduces CO_2 emissions and promotes adaptation to reduce risks to marine fishing and farming industries from ocean acidification.

Support reforming the Fisheries Act and Marine Protected Areas legislation to increase the resilience of our oceans to cope with unavoidable ocean acidification.

THE PH SCALE



THE AVERAGE PH IN THE WORLD'S OCEANS HAS FALLEN TO AN AVERAGE OF 8.1, SO THE OCEANS ARE STILL ALKALINE BUT BECOMING MORE ACIDIC.

SECTION 1:

OCEANS ARE BECOMING MORE ACIDIC

What is Ocean Acidification?

Since the middle of the 18th century, growing global emissions of CO_2 from agriculture and industry have caused concentrations of CO_2 in the atmosphere to rise from 278 parts per million to more than 400. Rising levels of CO_2 are changing the chemistry of seawater in a process known as ocean acidification. The oceans have absorbed about a third of all the CO_2 created by human activities since the industrial revolution.[1]

On the pH scale that measures whether a solution is acidic or alkaline, pure fresh water sits in the middle with a neutral rating of 7.0. Any solution with a level below 7.0 is acidic and anything higher than 7.0 is alkaline.

The pH of our oceans averaged 8.2 before industrialisation caused atmospheric CO_2 to rise. Already, the average pH in the world's oceans has fallen to an average of 8.1, so the oceans are still alkaline but becoming more acidic.[2]

A reduction of 0.1 might seem insignificant, but the pH scale is logarithmic, similar to the magnitude scale for earthquakes, so this drop equates to a 26% rise in acidity.

Acidification's chemical process

The pH (potential hydrogen) scale measures the concentration of hydrogen ions in a liquid – as the concentration of hydrogen ions rises, the solution becomes more acidic.

When CO_2 in the air diffuses into seawater, carbonic acid is created. This acid then decomposes into hydrogen ions and bicarbonate ions. Almost all the hydrogen ions then combine with carbonate ions to form more bicarbonate.

The depletion of carbonate ions in this process lowers the concentration of aragonite and calcite, two carbonate minerals vital for shell and skeleton building in many marine organisms.[3]

Past acidification events

Geological and fossil records indicate previous naturally occurring rises in acidification, including mass extinctions in the Permian Period about 251 million years ago.[4]

Models suggest that, when concentrations of CO_2 rose sharply during the Paleocene-Eocene Thermal Maximum (PETM) 55.3 million years ago, ocean pH declined by up to 0.45 units.

What was the effect of this warming and increase in ocean acidity? Warm-water species moved towards higher latitudes during the PETM, and the composition of plankton communities changed. Mass extinctions of species of foraminifera, single-cell organisms with external or internal shells, occurred. In coastal waters, corals and calcifying algae, types of seaweed that incorporate calcium carbonate, were replaced by other species.[5]

One significant difference between the PETM and today is that the rise in atmospheric CO_2 during the PETM was much slower than the rise we are experiencing now.

Ocean pH levels vary in different conditions

The pH levels in the world's oceans vary considerably, with surface waters ranging from 7.95 to 8.35 depending on season, currents, temperature, and other natural processes.[6]

Temperature is a major driver because cold water can absorb more CO_2 than warm water, so New Zealand's southern waters generally have a lower pH than northern seas.

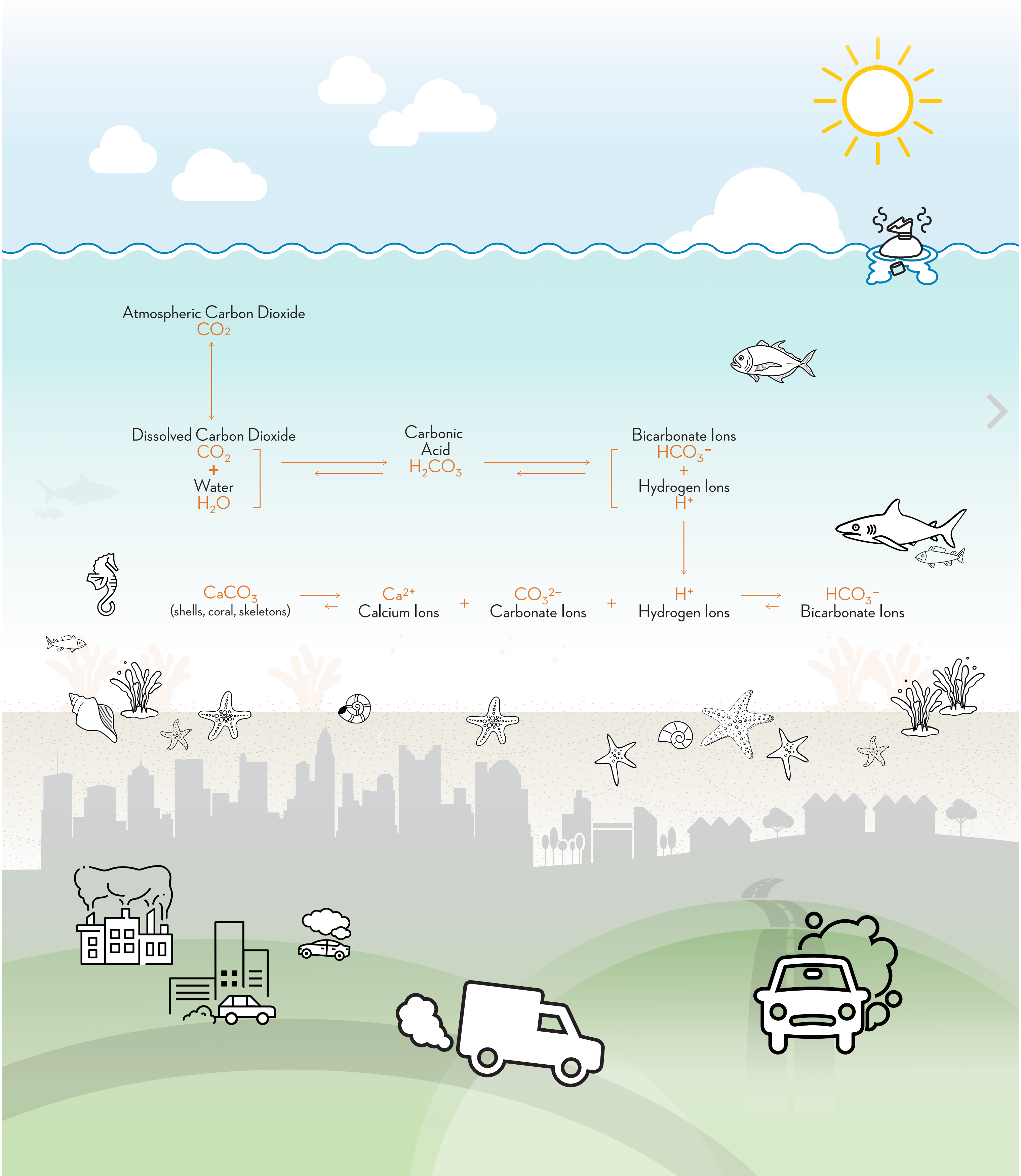
The variations in pH levels seen in ocean waters tend to be even more marked in coastal waters, where the influence of the land and human activity play a stronger role. Rivers discharge pollutants, organic material, and nutrients such as nitrogen and phosphorus, all of which stimulate bacterial CO_2 production.

Algal blooms and the presence of seaweeds and sea grasses also have a localised effect on coastal pH levels.

These can also vary widely over a 24-hour period from the contrasting effects of photosynthesis during daylight hours and respiration at night. Plants and some other organisms generate oxygen during the day by using sunlight to synthesise nutrients from CO_2 and water. At night, plants and other photosynthesising organisms convert stored energy into a usable form by consuming oxygen and emitting CO_2.

In New Zealand, the Munida time series has been measuring pH and other characteristics relating to carbonate chemistry since 1998. Samples are taken every two months at eight different points in a 65km-long line off the Otago coast that includes coastal, sub-tropical, and sub-Antarctic bodies of surface water and one deep (500m) measurement. The pH of the sub-Antarctic surface water declined by an annual average of 0.0013 pH units a year between 1998 and 2012, which was consistent with the trend of increased atmospheric CO_2 measured in New Zealand.[7]

OCEAN ACIDIFICATION CHEMISTRY



Data from the New Zealand Ocean Acidification Observing Network (NZOA-ON), which monitors pH at 14 coastal sites around the country, reflect the greater variability of coastal waters compared with the open ocean. The NZOA-ON figures show that pH levels have ranged from nearly 8.4 to below 7.7.[8]

Is acidification apparent in the deep ocean?

The pH level varies in different water masses and at different depths. The system of ocean currents known as the global conveyer belt transports seawater around the world.

As water approaches the North Pole, it cools and sinks into the deep ocean and is carried south towards Antarctica, where additional deep water is formed. Later, as it flows back into the Indian, Pacific, and Atlantic oceans, it warms again and rises towards the surface. Water can take an estimated 1000 years to complete a full circuit of the global conveyer belt.

CO_2 from anthropogenic sources enters the ocean at the surface and, because of the long cycle of the global conveyer belt, the impact of acidification is largely confined at present to the upper 200m to 500m of ocean waters.[9] However, CO_2 from anthropogenic sources has been detected as deep as 3000m in the North Atlantic.[10]

Future projections for acidification

Ocean acidification will continue to intensify in coming decades as CO_2 levels in the atmosphere continue to rise. The degree of acidification and whether pH levels can rise again will depend on how quickly the world responds to the need to cut the output of CO_2 and other greenhouse gases.

The Intergovernmental Panel on Climate Change (IPCC) has developed four Representative Concentration Pathways (RCPs) to represent different scenarios for future CO_2 emissions. At one extreme, the RCP2.6 scenario represents the best case scenario of the world's greenhouse gas emissions peaking in about 2020 then falling sharply. Under this scenario, pH would continue to fall until mid-century, followed by a slow recovery.

In the two middle scenarios – RCP4.5 and RCP6.0 – CO_2 emissions peak in about 2050 and 2075 respectively. In the RCP8.5 "business as usual" scenario, emissions keep rising throughout this century.[11]

Under projections for the New Zealand Exclusive Economic Zone (EEZ) under the RCP8.5 scenario, average open ocean pH levels would fall to 7.95 by 2050 and to 7.75 by 2100. The fall of 0.33 from current mean level of 8.08 by 2100 represents a 116% increase in acidity.[12]

Aragonite and calcite saturation

One of the consequences of reduced pH and lower levels of carbonate ions in seawater is lower saturation levels of the calcium carbonate minerals aragonite and calcite.

Calcifying organisms, such as shellfish, corals, sea urchins, and some types of plankton, use either or sometimes both of these minerals to form shells or structures.

Below certain depths, the ocean is no longer supersaturated in aragonite and calcite, because colder temperatures and increased pressure make carbonate more soluble. The depth at which sea water changes from being supersaturated to undersaturated in aragonite or calcite is known as the saturation horizon. Below the saturation horizon – which is shallower for the more soluble aragonite than calcite – these minerals can begin to dissolve.

The aragonite saturation horizon (ASH) varies in New Zealand waters, depending on the characteristics of different water masses, including temperature and the concentration of dissolved inorganic carbon – CO_2, carbonic acid, bicarbonate, and carbonate. In warmer waters, particularly north of the Chatham Rise, which extends eastwards from the Canterbury coast to the Chatham Islands, the ASH lies about 1300m below the sea's surface. In colder sub-Antarctic waters, it is about 900m.

By mid-century, the ASH is projected to become shallower, at 820m to 950m throughout most of New Zealand's EEZ.[13]

If CO_2 emissions continue to grow, surface waters in polar regions are projected to be undersaturated with aragonite by the end of century, along with 70% of the Southern Ocean, where temporary undersaturation events may be experienced as early as 2030.[14]

OCEAN ACIDIFICATION IN NEW ZEALAND

Tracking acidification in NZ waters

New Zealand scientists have been tracking the growing acidification of the ocean around New Zealand waters since 1998 in the longest-running monitoring programme in the Southern Hemisphere.

The Munida time series – named after the University of Otago vessel that was originally used in the monitoring programme – collects water samples every two months along a 65km-long line off the Otago coast. As well as pH, the measurements include total inorganic carbon and other parameters.

Measurements along the line can vary considerably on a single day because the monitoring points include coastal waters, modified sub-tropical waters, and sub-Antarctic waters. The programme is led by NIWA marine chemist Dr Kim Currie.

"Depending on the time of year and the conditions, it can be quite a sharp boundary. Sometimes, within a kilometre or two, the water temperature will drop several degrees, and the salinity and the pH will change as well," Dr Currie says.

It took more than a decade to distinguish the trend of falling pH because of acidification from the natural variability. But the decline is in line with similar monitoring in the Northern Hemisphere and with the changes in atmospheric CO_2 measured by NIWA at Baring Head near Wellington.

Dr Currie also heads New Zealand Ocean Acidification – Observation Network, which is recording pH levels at 14 coastal sites around New Zealand.

Photo: Kim Currie (right) with Otago University student on Munida time series. © Dave Allen, NIWA.

SECTION 2:

ACIDIFICATION EFFECTS ON OCEAN PRODUCTIVITY

Impact on primary production

Ocean acidification and other disruptions to the oceans related to climate change pose risks for the entire food chain, starting at the base where phytoplankton, seaweeds, other forms of algae, and seagrasses transform inorganic nutrients and light into biomass through photosynthesis.

Phytoplankton include thousands of microscopic species. Major groups include cyanobacteria, diatoms, dinoflagellates, green algae, and coccolithophores. The transformation of inorganic carbon into organic carbon by phytoplankton through photosynthesis ensures the oceans act as a carbon sink, releasing less carbon back into the atmosphere than they absorb.

Phytoplankton live in sunlit surface waters and either decompose and sink through the ocean or are consumed by zooplankton, which include microscopic animals drifting in the oceans and the larval stages of other marine creatures. Fish or bacteria consume much of this organic matter, but some sinks to the ocean floor, acting as a store for carbon. Although CO_2 is vital to phytoplankton because they are photosynthesisers, rising levels of CO_2 will have varying impacts on different species.[15]

Some seaweeds, other algae, and species of phytoplankton will likely benefit from higher CO_2, but some calcifying marine species, such as coralline algae and the phytoplankton coccolithophores, will be at risk.

Calcifying phytoplankton

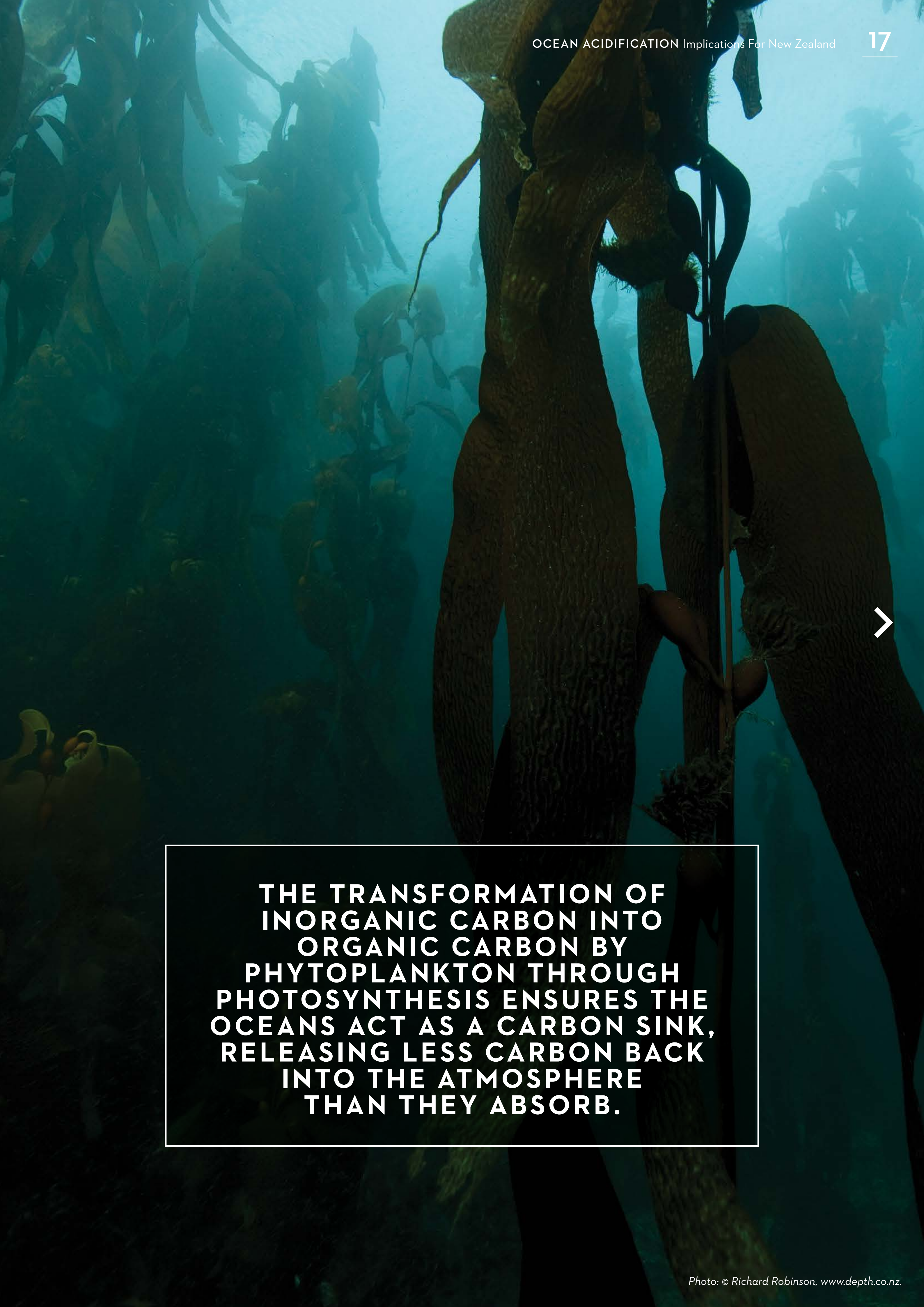
About 200 species of coccolithophores are found throughout the world's oceans, and these are one of the leading producers of calcite in the ocean. These microscopic phytoplankton are surrounded by protective shells formed by calcite plates and are a major source of long-term storage of carbon at the bottom of the ocean.

Chalk and many types of limestone are largely composed of coccolithophore fossils. Studies have shown that their response to lower pH is highly variable, depending on species and strain, and that other factors such as temperature and nutrient supply may also alter their response.

Early laboratory experiments indicated that the protective calcite plates might be damaged by low pH conditions, although other results have been contradictory. A 12-month study in New Zealand suggests that the most common species found in New Zealand and globally, Emiliana huxleyi, may have some capacity to adapt to higher CO_2 conditions over time.[16]

Macroalgae and seagrasses

Seagrasses generally grow more strongly in higher CO_2 conditions according to studies, and non-calcifying seaweeds have also shown positive responses.[17] But, as calcifiers, some species of coralline algae are likely to be more vulnerable to the effects of acidification.



THE TRANSFORMATION OF INORGANIC CARBON INTO ORGANIC CARBON BY PHYTOPLANKTON THROUGH PHOTOSYNTHESIS ENSURES THE OCEANS ACT AS A CARBON SINK, RELEASING LESS CARBON BACK INTO THE ATMOSPHERE THAN THEY ABSORB.

Photo: © Richard Robinson, www.depth.co.nz.

What does acidification mean for phytoplankton?

Most of us are barely aware of the microscopic phytoplankton in our oceans, but they are the foundation of the marine food chain, as well as consuming as much CO2 and creating at least as much oxygen as all the forests and land plants combined. Like land plants, they are photosynthesisers, using sunlight, CO2, and nutrients to create organic compounds.

Professor Cliff Law, NIWA's Principal Scientist for Marine Biogeochemistry and coordinator of ocean-atmosphere research, has researched the likely impact of ocean acidification on phytoplankton as part of the four-year Coastal Acidification: Rate, Impacts and Management (CARIM) project.

At NIWA's Wellington headquarters, Professor Law and his team have been studying phytoplankton communities drawn from the capital's harbour in nine 4000L containers known as mesocosms. Some of the containers were exposed to pH levels and temperatures expected under a "business as usual" scenario for greenhouse gas emissions by the end of this century and compared with those left under current conditions.

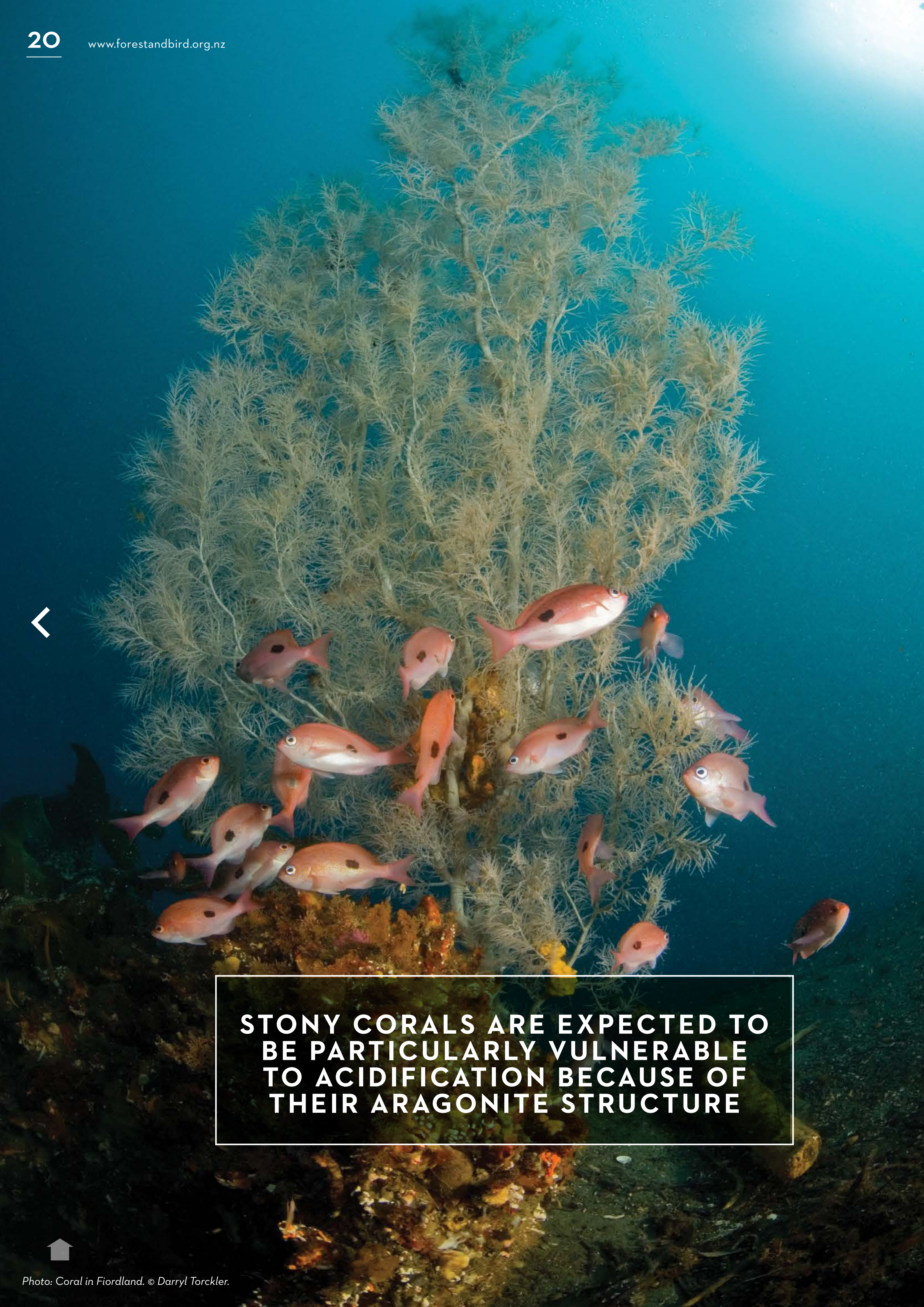
"We do these experiments in the mesocosms because they're halfway between the real world and the laboratory. It's a full coastal plankton community we're dealing with, so we get much more realistic responses than in the laboratory," Professor Law says.

Overall, changing pH had relatively little impact on the total quantity, or biomass, of phytoplankton, but there was an increase in biomass under warmer temperatures. Under lower pH and warmer temperatures, the diversity of different species of phytoplankton declined, raising questions about the flow-on effects for the marine food web if acidification and warming had the same impact in nature.

Another observation suggested that zooplankton, which consume phytoplankton and are the next link in the food chain, grazed less efficiently under future conditions, which could also potentially have cascading effects through the marine food web.

There are also possible climate implications. The research showed a decline in the production by the phytoplankton community of the gas dimethyl sulphide (DMS) which is speculated to influence cloud formation in the atmosphere, Professor Law says. "One potential interpretation is that acidification and warming could decrease the amount of cloud cover, which would accelerate the rate of warming further, but this is speculative because the links between DMS and cloud formation are very complex and difficult to nail down."

Photo: Cliff Law. © Dave Allen, NIWA.



STONY CORALS ARE EXPECTED TO BE PARTICULARLY VULNERABLE TO ACIDIFICATION BECAUSE OF THEIR ARAGONITE STRUCTURE

Photo: Coral in Fiordland. © Darryl Torckler.

SECTION 3:

EFFECTS ON MARINE SPECIES

Physiological impacts on marine species

A primary area of research into ocean acidification is on its physiological impact on different marine species. It has been recognised that species that form shells or skeletons of carbonate would be vulnerable, but more-recent studies have also shown that high CO2 levels disrupt the neurological systems of some fish species.

The larvae of marine species have been a focus of attention because this life stage is generally believed to be the most vulnerable to the effects of acidification. Shellfish larvae, for example, create their first shell and respond to chemical cues on where to settle as their planktonic stage ends.

Acidification suppresses shell growth and can result in deformed shells. Apart from the risk of increased mortality, larvae may be exposed to predators for longer periods if they develop more slowly.[18]

Calcifying organisms

Calcifying organisms have shells or skeletons constructed of aragonite or calcite. These include the planktonic mollusc species pteropods, other shellfish, coral, and echinoderms such as sea urchins.

As levels of CO2 in the ocean rise and pH levels fall, many species will find it more difficult to produce carbonate structures, although research shows that the level of vulnerability can vary widely and may also depend on other stressors, such as ocean warming.

These calcifying species use internal biological mechanisms to help form solid carbonate by raising the pH levels above that of their body fluids and surrounding water. Growth or reproduction may be hampered under low pH as more energy is diverted to making shells.[19]

Pteropods, commonly known as sea butterflies, are near transparent sea snails that use their feet for swimming and are an important link in the ocean food chain. Studies have shown that they are vulnerable to acidification, which causes pitting and weakening of their aragonite shells.

Shell damage in pteropods has already been found in marine environments along the West Coast of the US, where upwelling of low pH waters is providing a preview of some of the likely impacts of increasing acidification.[20] Similar shell damage has been found in sub-Arctic and Mediterranean species as well as in the Southern Ocean.[21] [22] The damage to the pteropod shells occurs as the saturation state for aragonite drops towards undersaturated levels.

Shellfish

The shellfish aquaculture industry sat up and took notice a decade ago after scientists established a link between acidified waters in the US Pacific Northwest and the deaths of up to 80% of larvae at oyster hatcheries from 2005. The region is subject to colder, more-acidic waters rising from the deep ocean because of the effect of currents and prevailing winds, and these conditions have been aggravated by the impact of ocean acidification.

The Whiskey Creek Shellfish Hatchery in Oregon State worked with scientists to establish the link between the high larval mortality rate and the low pH and aragonite saturation levels. The aragonite saturation levels at the site of the hatchery are highly variable, so the solution was to pump water into the hatchery tanks only when conditions were optimal for larvae survival.[23]

There has since been a strong focus on the potential impact on shellfish in studies, many of which have indicated the vulnerability of molluscs at the larval stage. Many early studies were short term and did not consider other stressors, such as temperature, food quality, and potential adaptability.[24] In recent years, research has broadened to look at other stressors, especially warming, ecological interactions, and adaptability.[25]

No signs of damage to shellfish by acidified waters in natural environments have yet been reported in New Zealand, but the US experience serves as a warning about what the future could hold.

Cold-water corals

Extensive research has been done on the role of acidification and warming seas in bleaching tropical and sub-tropical corals found in shallow waters. Less is known about the deep-sea corals found in the cooler waters in temperate regions such as New Zealand, but these are also vulnerable to acidification.[26]

Stony coral species from the *Scleractinia* order are a dominant group in the New Zealand EEZ. Black corals are also abundant in the fjords, and deep-sea and gorgonian corals are also common.[27] Stony corals and some other cold-water species are expected to be particularly vulnerable to acidification because of their aragonite structure, while the gorgonian corals have high levels of magnesium calcite, an even more soluble form of calcite.[28]

Most deep-water corals are found above the ASH in the EEZ. As the horizon becomes shallower from acidification, only the habitats at the top of the Chatham Rise and Campbell Plateau, and a few seamounts along the Kermadec and Macquarie ridges, are expected to remain above the ASH by the end of the century.[29] Some species may be more vulnerable than others, and other factors, including oxygen and food supply, may also play a role in determining survival.

Echinoderms

Echinoderms, a calcifying group that includes sea urchins and starfish, have also demonstrated vulnerability to acidification. A synthesis of studies on 15 different sea urchin larvae species showed that 13 grew less and had abnormalities at acidity levels expected by the end of this century.[30] A 2016 study at a low pH, high CO_2 underwater volcanic vent in Papua New Guinea also showed reduced growth and abnormalities when larvae were placed near the vent.[31]

Photo: © Rob Stewart, NIWA.

Crustaceans and cephalopods

In general, crustaceans – such as crabs, crayfish, and prawns – and cephalopods – such as squid, octopuses, and cuttlefish – are seen as less vulnerable to acidification than the calcifying species.[32]

But a study of the eggs and hatchlings of the Atlantic longfin squid under elevated CO_2 conditions showed abnormalities to their statoliths, an internal structure made of aragonite and used for balance and orientation. However, many species of squid experience wide-ranging conditions, including high CO_2, in their lifetimes, and more research is needed to determine where acidification thresholds lie.[33]

Impacts on fish

In recent years, scientists have discovered that acidification can have a dramatic effect on the behaviour of some fish species. Studies of the juveniles of coral reef species in laboratories and at natural CO_2 seeps in Papua New Guinea showed that, under elevated CO_2 levels, they were attracted to, rather than repelled by, the odour of predators and had difficulty in finding suitable habitats and selecting prey.[34] The physiological changes involved appear to be caused by interference to the brain neurotransmitter function, affecting their senses. Studies have shown differences between species in sensitivity to higher CO_2 levels and the ability to adapt to them, which has implications for the composition of fish communities.[35] Similar effects have been found in some studies of fish from temperate waters, such as the three-spined stickleback, a common coastal fish in the Northern Hemisphere.[36]
A study of Atlantic cod larvae under low pH conditions expected by the end of the century in a “business as usual” scenario (RCP8.5) showed a doubling of daily death rates during the first 25 days after hatching.[37]

Photo: © Darryl Torckler.

OCEAN ACIDIFICATION IN NEW ZEALAND

Research in nature's lab

One of the more difficult tasks for scientists investigating ocean acidification is replicating natural conditions when studying the likely impact of future lower pH levels and higher CO_2. However, there are some natural environments where it is possible to glimpse into the future.

Marine scientist Dr Miles Lamare, an Associate Professor at Otago University, and two fellow scientists investigated the impact of high CO_2 on sea urchin larvae at volcanic CO_2 vents at a reef in Papua New Guinea. Larvae they moved to the vents – where pH was 7.50–7.72, compared with 7.89–7.92 in ambient conditions further away from the vents – grew more slowly and had more abnormalities.[38]

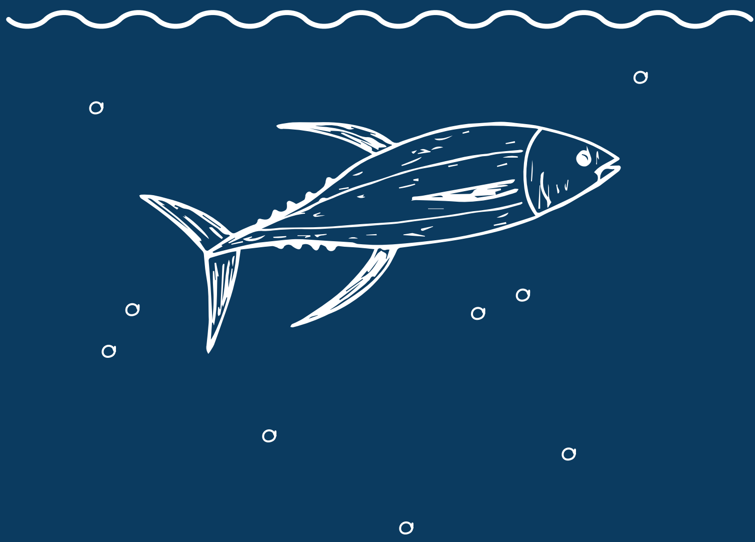
"CO_2 vents may be a small microcosm of what a high CO_2 ocean may look like in the future. People can go there and look at the abundance of different groups of species and see which ones have disappeared or declined and how the corals have been affected," he says.

NIWA marine ecologist Dr Vonda Cummings and colleagues have examined the effects of acidification on common Antarctic shellfish, including the marine bivalve *Laternula elliptica*. While the mollusc was able to survive greater acidification over a relatively short period, there were signs it required more energy to do so, causing stress in adults.[39] Furthermore, larvae reared at low pH were also affected, with slower growth rates in the shell forming stages[40] and lower shell quality and integrity.[41]

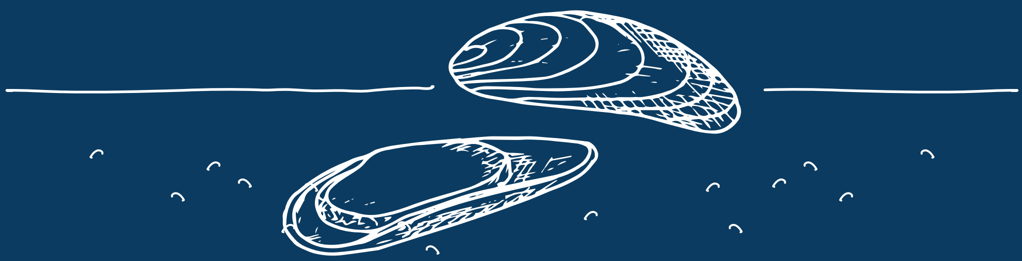
Dr Cummings was also involved in studies on microalgae living attached to the underside of sea ice. These showed that, while the algae used the extra CO_2, the pH remained low, a potential concern for organisms in this habitat.[42]

"Antarctic studies are useful for investigating the effect of reduced pH on an organism's physiology, because it's a relatively pristine system – there's no influence of inputs from the land at our remote study sites, and the pH does not fluctuate so much as elsewhere. Because the water is so cold, there is more dissolved CO_2, so it's already pretty close to being undersaturated in carbonate," she said.

Photo: Marine scientist Dr Miles Lamare diving. © Miles Lamare.



SHELLFISH PLAY AN IMPORTANT ROLE IN FILTERING ORGANIC MATTER AND DEPOSITING SEDIMENT AND NUTRIENTS ON THE SEAFLOOR, WHERE THEY ARE CONSUMED BY MICROBES



SECTION 4:

ACIDIFICATION IMPACTS ON MARINE ENVIRONMENT

Risks to ocean productivity

Ocean acidification impacts have the potential to affect species throughout marine ecosystems, with knock-on consequences for entire food chains.

Some of the effects will be direct, caused by intolerance to elevated CO2 levels and declining carbonate saturation. More indirect effects will include changes to the quantity and composition of food and altered habitats. The interactions between all of these factors are complex and the consequences difficult to predict.[43]

Acidification will alter the availability of carbonate for calcifying organisms and the behaviour of fish species. But other changes, such as rising water temperatures, the expansion of low oxygen areas, and changes in nutrient availability, will also influence likely reactions to acidification.

Coastal ecosystems

The productivity of coastal ecosystems will also come under pressure from acidification. The influence of nutrients from the land and the ability of the sun to penetrate to photosynthesising species on the seafloor in shallow areas means that coastal areas are more productive than oceans. In shallow coastal seas, sinking organic matter falls quickly to the seafloor where animals and bacteria can recycle it.

Shellfish, for example, play an important role in filtering organic matter and depositing sediment and nutrients on the seafloor, where they are consumed by microbes. Some of these microbes convert nutrients into nitrogen gas, which is released back into the atmosphere.

This process can help prevent eutrophication, where excess nutrients form algal blooms, which can lead to hypoxia among other impacts. Acidification and warming, along with human impacts such as pollution and excess nutrients entering coastal waters, can upset the balance of coastal ecosystems.

Disrupted food webs

Pelagic pteropod molluscs, which have shown sensitivity to falling aragonite saturation, are an important element of the food web in the waters around New Zealand and particularly in the Southern Ocean. If their numbers were to decline because of acidification, there would be cascading effects on other levels of the food chain.

Coralline algae, a calcifying macroalgae vulnerable to low pH, play a critical role in the settlement of the larvae of paua and other abalone species. As they settle on the sea floor during their transformation from larvae to adult form, the larvae respond to a chemical cue from the algae.[44] Any decline in coralline algae and the chemical cues they provide to paua raises questions about the impact on paua populations.

Although acidification and other climate change impacts are expected to affect the productivity of the oceans, the consequences are not clear. The adaptive ability of species will vary, but it is clear there are severe risks for ocean ecosystems and food webs, especially under the “business as usual” RCP8.5 scenario.


OCEAN ACIDIFICATION
IN NEW ZEALAND

Breeding mussels for the future

Green-lipped mussels are New Zealand's most significant aquaculture product, worth about $300 million a year. So it's natural that concerns about the impact of ocean acidification on shellfish would receive a lot of attention in the mussel industry.

Because of the economic importance of the mussel industry, much had already been learned about the life cycle of mussels and work had been carried out on maximising growth and financial returns through selective breeding.

Now the Nelson-based independent science organisation Cawthron Institute is applying that selective breeding knowledge to ocean acidification and looking for strains or families of the shellfish that will be more resistant to the effects of acidification as part of the CARIM project, says Cawthron research scientist Dr Norman Ragg.

The aim of the research is to see what natural resilience green-lipped mussels have to acidification and discover the biological processes that provide this resilience. Cawthron scientists have generated 96 different families to see if some are more resilient than others and to also determine if exposure to low pH conditions in one generation can produce added resilience in following generations.

"We have been excited to see preliminary results that suggest that both the genetics and the life experiences of mussel parents can potentially improve the resilience of their offspring. This is good news for the species as a whole and introduces a number of new options for marine farmers to consider to help 'future-proof' their stock" says Dr Ragg.

Photo: Mussel farm. © Darryl Torckler.

SECTION 5:

WHAT IS HAPPENING IN NEW ZEALAND WATERS?

The ocean around New Zealand

New Zealand is a country closely tied to the ocean, with an EEZ 15 times larger than our land mass. The ocean and coastal waters are key elements of our environment, cultural life, and economy. Today, seafood products are our sixth-largest merchandise export, and the industry is a major employer.

New Zealand's EEZ, the 200 nautical mile zone lying outside the 12 nautical mile territorial waters, is one of the largest in the world at four million square kilometres. The EEZ includes 62 distinct marine habitats – from sub-tropical waters in the far north to deep sub-Antarctic waters in the south.[45]

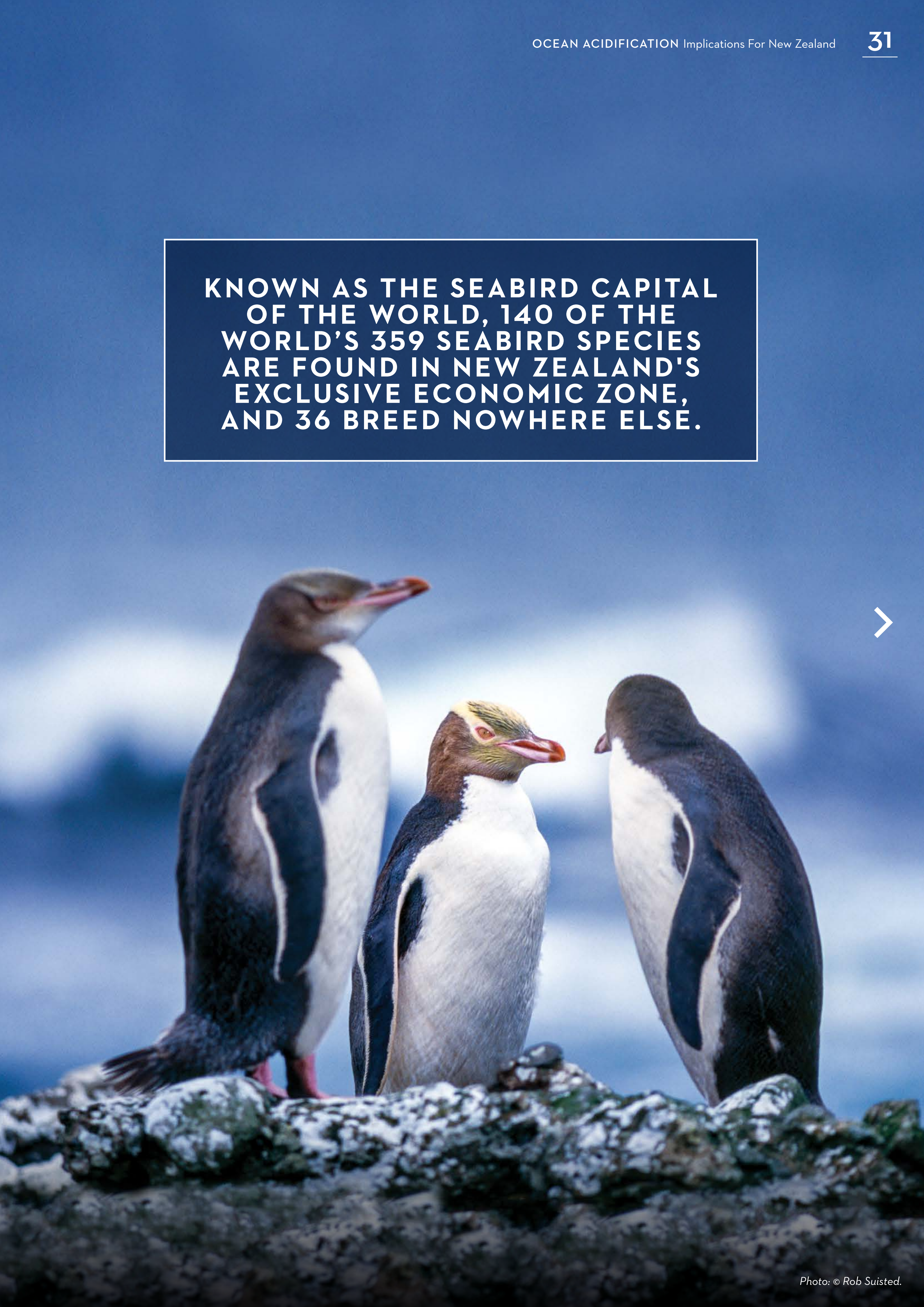
Extensive shallow shelf areas can be found on the Challenger Plateau and Lord Howe Rise to the northwest and the Chatham Rise and Campbell Plateau to the southeast. Warm sub-tropical waters and cooler sub-Antarctic masses meet at the sub-tropical front south of the New Zealand mainland and along the Chatham Rise, to the east of the South Island. The mixing of the warmer sub-tropical waters and nutrient-rich sub-Antarctic water masses encourages the growth of phytoplankton and other species that feed on them.[46] The neighbouring Southern Ocean accounts for nearly 40% of all the anthropogenic CO_2 absorbed by the world's oceans.

New Zealand waters are home to Maui's dolphin, the world's smallest and rarest sub-species of dolphin, one of the world's rarest sea lions, and the yellow-eyed penguin, also believed to be the world's rarest.

Known as the seabird capital of the world, 140 of the world's 359 seabird species are found in New Zealand's EEZ, and 36 breed nowhere else.

Altogether, New Zealand has 86 breeding species, of which 32 are threatened with extinction, along with eight out of 14 shorebird species.[47] [48] New Zealand waters are also a global hotspot for cold-water corals.[49]

Our surrounding ocean and coastal waters provide New Zealanders with ecosystem services that include climate regulation, oxygen production, and the capture and processing of sediment, excess nutrients, and pollution produced on the land. The seas of the EEZ absorb more CO_2 than all our forests, according to provisional estimates, and provide us with important raw materials, food, and opportunities for recreation.[50]



KNOWN AS THE SEABIRD CAPITAL OF THE WORLD, 140 OF THE WORLD'S 359 SEABIRD SPECIES ARE FOUND IN NEW ZEALAND'S EXCLUSIVE ECONOMIC ZONE, AND 36 BREED NOWHERE ELSE.

Photo: © Rob Suisted.

Effects on phytoplankton

The most productive areas for phytoplankton in New Zealand are along the Chatham Rise and on the Subtropical Front in the Tasman Sea. Both support rich marine ecosystems and important commercial fisheries.

While studies of phytoplankton have shown very mixed results, increasing acidification may cause changes in plankton communities and diversity, with implications for food webs.[51]

Studies of plankton blooms from waters around the Chatham Rise showed that bacterial composition, production, and abundance did not change greatly when they were subjected to lower pH but that there was greater bacterial enzyme activity. This could increase the rate of decomposition of organic carbon by bacteria, resulting in more CO_2 being released back into the atmosphere rather than the carbon being deposited on the seafloor.

Increased enzyme activity could also have implications for food quality and nutrient availability in the oceans.[52] However, the complexity of these processes and the effects of acidification on different organisms mean outcomes are difficult to predict.

Threatened habitats

Cold-water corals are found all around New Zealand and provide important habitats for other marine species, including molluscs, crustaceans, and juvenile and adult fish. The Chatham Rise is an area rich in corals and one of the richest fishing grounds in the EEZ.[53]

Most cold-water corals are found between 200m and 1200m deep.[54] Because some of the Chatham Rise corals are found at relatively shallow depths, they are likely to be less vulnerable to the effects of acidification and a rising saturation horizon than those found in many other regions.

Marine bryozoans, single-cell animals that form colonies with a coral-like appearance on the sea floor, are predominantly calcifiers and are found all around the New Zealand coast and in the ocean. Along with species of calcifying sponges, they also provide important habitats for other species but are potentially vulnerable to acidification.

Impacts on fisheries and aquaculture

Ocean acidification and other climate change impacts pose huge risks for New Zealand's commercial fisheries and aquaculture industry, which rely on healthy coastal and ocean ecosystems for their success.

New Zealand earned $1.82 billion from nearly 267,901 tonnes of seafood exports in 2018.[55] The total commercial harvest was about 600,000 tonnes. The industry employs 13,000 full-time workers, and 123 species are commercially harvested.[56]

In aquaculture, which is dominated by green-lipped mussels, Pacific oysters, and salmon, export revenue of $406 million was earned in the year to June 2018.[57] More than 3000 people work in the industry.[58]

Risks to shellfish aquaculture from ocean acidification are well recognised, and studies have tried to assess the risks for key New Zealand commercial species such as green-lipped mussels, Pacific oysters, and mostly wild-caught paua. Green-lipped mussels, for example, have shells made entirely from the more-soluble aragonite, while oysters have calcite shells and paua shells consist of both aragonite and calcite.

Studies of paua have shown that low pH caused by high levels of CO_2 can restrict the growth of juveniles and shell formation.[59] Other experiments have shown pitting of live paua shells caused by lower pH levels and significant damage to empty shells, which suggests that paua can maintain shell condition through biological processes but at an energy cost.[60 61]

Mussel larvae are vulnerable when they are forming their first shell, and a study of the effect of pH at an extreme level of less than 7.5 resulted in reduced growth and shell malformation. Studies are being carried out in New Zealand to find out whether particular strains of green-lipped mussels and paua are more resistant to the effects of acidification.[62]

Fish species and acidification

Little research has so far been carried out of the potential impact of acidification and warming on New Zealand fish species.

A study of yellowtail kingfish larvae in New Zealand showed that elevated levels of dissolved CO_2 led to larvae swimming less distance and at a lower average speed when startled. Higher temperatures appeared to have more of an impact than CO_2, with a slightly lower survival rate of larvae, although the survivors' growth and development was faster.[63]

Another study did not show any change in the boldness or risky behaviour of the kingfish larvae under higher CO_2 levels, unlike some studies of species in other countries. However, higher CO_2 levels did increase the oxygen uptake of resting larvae, indicating a higher energy cost involved in adapting to these conditions.[64]

Similar studies were also being done on snapper larvae to find out more about how they respond to elevated CO_2 and temperature levels.

Our fish species and acidification

NIWA marine ecologist Dr Darren Parsons has been working with other researchers studying kingfish and snapper to find out how their larvae may be affected by more-acidic seas and warming. These were the first such studies of fish species in New Zealand.

Overseas studies have shown that the sensory behaviour of some fish is affected by high CO_2 conditions, although the effects have varied widely among different species. These studies have focused mainly on tropical reef fish and Northern Hemisphere species, with some showing that high CO_2 causes behavioural and sensory system effects, such as being attracted to, rather than repelled by, the odour of predators.

Kingfish were chosen for the initial New Zealand-based research because few large pelagic fish had been studied before and because they were already being reared in captivity at NIWA's Bream Bay marine science centre south of Whangarei, Dr Parsons said. Eggs and larvae were raised in tanks under different combinations of temperature and CO_2 levels at current levels and what might be expected by the end of the century if greenhouse gas emissions continue to grow.

One of the trials was to see how the larvae responded to being startled. "The fish raised under the warmer water had a faster response time and swum away from that stimulus at a higher maximum speed, whereas the fish with the elevated CO_2 swam a reduced distance away from that stimulus. Maybe the elevated CO_2 will have quite dramatic consequences when they're encountering predators in the natural environment, but we really just don't know."

The larvae had slightly lower survival rate in the warmer water, although the surviving fish grew faster, reflecting their increased metabolic rate under higher temperatures. Similar studies were later carried out on the larvae of snapper, one of New Zealand's most important commercial and recreational fishing species, with results due to be published from the second half of 2019.

Dr Parsons added that it was difficult to determine the likely consequences of acidification and warming in a natural environment because the studies looked only at the direct impact of higher CO_2 and temperature on a single species in laboratory tanks.

"We want to be working towards broader ecosystem research where you're studying more than just one species and looking at how impacts flow on from one species to another through the food web."

Photo: Bream Bay. © Michael Cunningham, NIWA.

OCEAN ACIDIFICATION IN NEW ZEALAND

Our Surface waters

TEMPERATURE INCREASED BY

0.4–1.2

DEGREES C

SINCE

1981

THE RATE OF WARMING IN NZ'S SURFACE WATERS HAS VARIED IN DIFFERENT AREAS. WARMING HAS AMOUNTED TO ABOUT 0.4 TO 1.2°C SINCE 1981.

SECTION 6:

INTERACTION WITH CLIMATE CHANGE IMPACTS

The effects of ocean acidification will in many cases be amplified or modified by other impacts related to climate change, including rising sea temperatures. Warmer seas will lead to hypoxia or low oxygen concentrations in some regions and alter ecosystems. These changes add to the complexity of predicting the impact of acidification in the oceans and coastal waters.

Rising temperatures decrease the solubility of oxygen in water and increase the metabolic rate of animals and microbes, reducing the availability of oxygen in the ocean. Low oxygen areas are expected to expand, especially in temperate and sub-polar regions, leading to changes in the ecosystems that can be supported there.[65]

Globally, the ocean warmed at an average rate of almost 0.5 degrees C in the upper 75 metres in the 40 years to 2010.[66]

However, warming trends differ around the world and fluctuate in different seasons and years because of natural phenomena, including the El Nino-Southern Oscillation in the Pacific Ocean.

In our region, the southwest Pacific, there is expected to be a rise in the average surface water temperature of 1.0 degree C by mid-century. Under the RCP8.5 scenario, the temperature is projected to rise by 2.5 degrees C by the end of the century.

The western Tasman Sea could see warming of up to 4.0 degrees C by the end of the century from the East Australian Current extending its southward flow along the southeast Australian coast. This could also result in sea surface temperature rises of more than 3.0 degrees C in the northern Tasman Sea. Temperatures may rise by 2.5 degrees C on the eastern Chatham Rise, while the lowest temperature rises are expected in sub-Antarctic waters.[67]

In the surface waters around New Zealand, the rate of warming has varied depending on prevalent currents and the different water bodies flowing around the country. Warming has amounted to about 0.4 to 1.2 degrees C since 1981. The rate of warming has varied from decade to decade, but the trend is clear and will continue.[68]

Impact of warming and related changes

In polar regions, warming and the melting of ice are projected to cause an increase in net primary production (NPP), the useful chemical energy phytoplankton and algae produce through photosynthesis at the base of the food chain.. But this is likely to be more than offset by reductions in NPP in tropical and sub-tropical waters because of a reduction in available nutrients available to these organisms.[69]

There are wide regional differences globally in primary production depending on natural climate variability, currents, cloud cover, and nutrient availability. But modelling suggests an estimated fall of up to 9% in NPP globally in the open oceans by the end of the century under the RCP8.5 "business as usual" scenario, although there is uncertainty about this figure.[70]

Besides light and CO_2, nutrients are critical for phytoplankton growth. Macronutrients include nitrate, silicate, and phosphorus, and micronutrients (trace metals) such as zinc, cobalt, and iron can also be important.

Higher sea temperatures result in less mixing between the warmer surface water layer and colder layers deep in the ocean because of the increased difference in density. This increasing stratification makes it more difficult for nutrients to rise from deeper waters to the surface layer, affecting the availability of micronutrients such as iron to phytoplankton in many regions.[71] Under the RCP8.5 scenario, this increasing stratification may affect the productivity of the eastern Chatham Rise by the end of the century.[72]

Warming may initially enhance phytoplankton production, but over time some species will reach their temperature tolerance limit, leading to some being replaced and shifts in their geographic range. This may result in changes to the communities of phytoplankton. Already, there is evidence of increasing proportions of smaller phytoplankton species in warmer seas compared with colder regions. [73]

In coastal areas, acidification and warming combined with nutrient run-off from the land may increase the risk of algal blooms, some of which are toxic.

Increased microbial activity as the blooms decompose can deplete oxygen, threatening marine life. Although these problems already occur, acidification and warming are likely to make these worse.

Macroalgae and seagrasses

Although non-calcifying seaweeds and seagrasses may grow more strongly in higher CO_2 conditions, any potential benefit could be offset by warming. Seagrasses and seaweeds have species-specific temperature tolerances, but generally those in temperate climates are believed to be more tolerant than those in polar and tropical climates.[74]

Around the world, sea temperature rises have been greater in coastal areas than in the open ocean, and these rises have had a negative impact on seagrass meadows. A decline in kelp forests has also been reported around the world, including in southern Australia, where kelp forests have been devastated by the advance of the warmer, nutrient-poor East Australian Current into eastern Tasmanian waters.

The advance of the warmer waters also brought an influx of long-spined sea urchins that had previously not tolerated the cooler southern waters.[75] The urchins feed on the kelp and are preventing kelp forests from re-establishing.

Seagrasses and kelp provide shelter and food for coastal marine communities, including molluscs, invertebrates, and fish. The juveniles of our most-prized eating fish, snapper, prefer harbours and bays containing seagrass meadows or kelp forests.

Kelp forests also help raise the pH in their immediate environment through photosynthesis, potentially providing refuge for other species, including calcifying macroalgae, from the effects of acidification.[76]

The impact of acidification and warming can be exacerbated by other stresses on ecosystems, such as overfishing. The fishing pressure on snapper and other predators, such as rock lobsters, has created kina barrens in some New Zealand coastal areas, particularly in the north.

The lack of predators causes an explosion in numbers of kina or sea urchins, stripping the surrounding area of kelp and other vegetation. The potential risks to kelp and seagrasses from acidification, warming, and other impacts, such as overfishing, can create a feedback loop, accelerating the decline of species and ecosystems.

IImpact of warming on fish and shellfish

The combined effects of natural climate variability and warming seas because of climate change have resulted in a shift of species towards the poles in recent decades. The distribution of many species of fish and invertebrates is expected to expand or shift pole-wards by tens of kilometres every decade.[77]

Many species have a lower tolerance to warming at particular periods of their life cycle, particularly in early life or when spawning as adults. Studies of fish have shown that body sizes have fallen because small individuals are more heat tolerant, and this trend is expected to continue as the seas warm further.[78] The timing of fish migrations has moved in line with warming. For example, pink salmon in Alaska are migrating two weeks earlier than four decades ago.

New Zealand experienced the impacts of warmer seas in the summer of 2017/18, when a marine heatwave saw sea temperatures rise two degrees or more above average in the Tasman Sea.[79] There were reports that the warmer seas resulted in kelp forests suffering substantial losses, substantial die-offs of shellfish on the Kapiti Coast, and losses of farmed salmon in farms in the Marlborough Sounds.

In September 2018, fishing companies cut their fishing quota by nearly a quarter in the West Coast hoki fishery because of declining numbers they said may have been attributable to the warmer waters in the Tasman Sea. The warmer surface sea conditions were a key reason for 2017/18 being the hottest New Zealand summer ever recorded.[80]

The role of hypoxia

The expansion of hypoxia or depleted oxygen in regions known as oxygen minimum zones and anoxic "dead zones" completely lacking in oxygen in recent decades is expected to continue in the future because of ocean warming and other changes. In coastal areas, in particular, the input of land-based nutrients resulting in algal blooms will amplify this trend. Hypoxia is a constraint on oxygen-dependent species that benefits anaerobic microbes, which do not require oxygen to grow.

Hypoxia tolerance varies among species, but the result would be a community shift to species tolerant to hypoxia, which in extreme cases would be dominated by microbes.[81]

Disrupted food webs

Climate change impacts have the potential to severely disrupt food webs from microscopic phytoplankton to the top predators, such as marine mammals, seabirds, and sharks. The timing of production peaks for phytoplankton in spring and summer is occurring earlier, with implications for other species further up the food chain.

In Antarctica, algae is the main source of food for shrimp-like krill, which in turn feed some of the largest animals in the world, including blue and humpback whales, as well as penguins, seals, seabirds, and fish.

The krill feed on algae found on the underneath of sea ice, but this source of food has declined as the sea ice has retreated on the western shelf of the Antarctic Peninsula. This has resulted in falls in the regional populations of krill and of one of their main predators, the Adelie penguin.[82]

Some of the key fish stocks in the Pacific Ocean have shifted because of climate change combined with natural climate variability in a trend that is expected to continue in the future. The distribution of tuna species such as skipjack, yellowfin, and South Pacific albacore has changed because of changes in sea temperature. Even species with a greater tolerance to temperature rises may be affected because of changes to the distribution of some of their key food sources.[83]

Marine mammals such as seals and sea lions, and breeding seabirds – many of which return to the same place to breed season after season – may struggle if their prey shifts because of climate change impacts. Some species of prey may also move to greater depths because of warming, forcing predators to use more energy in foraging.[84]

MARINE MAMMALS SUCH AS SEALS AND SEA LIONS, AND BREEDING SEABIRDS MAY STRUGGLE IF THEIR PREY SHIFTS BECAUSE OF CLIMATE CHANGE IMPACTS

Photo: Cape Kidnappers. © David Brooks.

SECTION 7:

MEETING THE CHALLENGE OF OCEAN ACIDIFICATION

Ocean acidification is happening already and will continue to intensify even if the world takes immediate action to cut greenhouse gas emissions.

Under the RCP2.6 scenario, greenhouse gas emissions would be cut from 2020 and would decline to levels last seen in the mid-20th century by 2050. Average air temperature rises would likely be restricted to 0.3 to 1.7 degrees C under this scenario,[85] and average ocean pH levels would start to rise again after troughing by the middle of this century. Nevertheless, under this scenario, pH would still be 0.06 to 0.07 units lower at the end of this century compared with current levels, representing a rise of 15% to 17% in acidity.

At the other extreme, under the RCP8.5 "business as usual" scenario, emissions would continue to rise during the century, and pH would likely fall by 0.30 to 0.33 units, more than a doubling of acidity. Given the risks to marine ecosystems from acidification and ocean warming, the only safe course is to start reducing carbon emissions immediately.

Some further acidification of the oceans and coastal waters is inevitable, and it is crucial we gain a better understanding of the consequences.

We already know enough to underline the importance of trying to rapidly lower emissions rather than carrying on with "business as usual".

Filling the knowledge gaps

When it comes to mitigation and adaptation strategies, global models do not tell us enough about the likely impacts in New Zealand waters. Our enormous EEZ and the many different ecosystems within it are characterised by different combinations of currents, climate, geochemistry, biological processes, and species. Each will be affected by acidification in different ways.

While it will never be possible to study everything in the EEZ, we will need to collect data to enable scientists to develop models that reflect the unique characteristics of key New Zealand marine environments and ecosystems. Without reliable data from observations in the present, it will be impossible to look into the future.

The Ministry of the Environment and Statistics New Zealand said in their *Our marine environment 2016* report that gaps in national data make it difficult to draw conclusions about the present state of important areas of New Zealand's marine environment. If we have insufficient information on key areas of our marine environment, it will be impossible to understand the profound changes that are under way and how best to adapt to them.

Alongside other research being carried out on the impact of ocean acidification in New Zealand, the Ministry of Business, Innovation and Employment funded a four-year programme of research – Coastal Acidification: Rate, Impacts and Management (CARIM). The programme, which is due to end in early 2020, looked at the impact of acidification on coastal environments and on important economic species such as mussels, paua, and snapper.

Other work has included experiments to see whether using empty shells as a source of carbonate and aeration can counter the effects of acidification at mussel farms.

It is important that a programme of research continues into the impact of acidification and warming in the ocean surrounding us and in the economically and environmentally important coastal areas.

Acidification and warming are changing chemical, physical, and biological processes in the ocean. Scientists realise that life in the ocean faces multiple stressors from anthropogenic change, and studies are increasingly trying to replicate the complexity of natural environments where possible to examine interactions between different organisms within ecosystems.

Habitats are highly variable due to factors that include currents, seasonal variability, temperature and pH ranges, chemical properties, and nutrient availability. Some species will be more adaptable than others, and all these factors taken together underline the complexity of predicting the outcome of increasing acidification and warming.

Reducing the risks

Future research will also be needed to investigate the impact on coastal environments of these multiple stressors, including acidification, warming, sedimentation, nutrient run-off from the land, and fishing pressure. Better planning processes for land use and coastal areas and the wider use of marine spatial planning will help to reduce these impacts.

Reducing stressors such as sedimentation, nutrient run-off, and excessive fishing pressure will help make coastal ecosystems more resilient to acidification and related threats. A network of Marine Protected Areas is also an important step in making ecosystems more resilient to the effects of rising CO2 levels.

One of the most complex and important areas of research will be to look at how the composition of ecosystems and food webs may change. These issues are crucial to how acidification will affect our marine environment and commercial fisheries.

The adaptability of individual species and the biological mechanisms they use to adapt is also a focus for scientists. Many species already face a range of different pH conditions, but what are the limits of their adaptability as acidity and temperatures exceed previous maximums?

Work is already being carried out for some key commercial species such as green-lipped mussels, paua, and snapper. There will be a need for more research into the potential implications for commercial fishing from acidification-induced behavioural changes to fish species and the impacts of warming on species distribution.

This research will also be important to inform decisions on the Quota Management System, which will need to take climate-change-related risks to fish stocks into account.

In coastal waters, the impacts from land-based activities, such as the nutrients and pollution flowing into the sea from rivers, need to be considered alongside acidification, particularly in considering possible mitigation and adaptation measures.

Conservation in a more acidic future

Acidification will also have implications for conservation planning. For example, scientists predict that areas of suitable habitat for deep-water corals in New Zealand's EEZ may sharply decline because of acidification. The Chatham Rise is expected to remain as suitable habitat for longer than many other areas, so new protections may be necessary for the Chatham Rise if other habitats disappear or become degraded.

Acidification also has implications for our native freshwater species that spend part of their life cycle at sea. These include longfin eels and the five species that are harvested in their juvenile form as whitebait. All of these species are already under pressure from such factors as habitat loss, dams, pollution, and fishing.

As a small country in a large ocean, New Zealand needs to face up to how acidification and related threats are changing our marine environment. When it comes to protecting our environment, economy, and future generations from acidification and climate-change-related threats, there is no dividing line between land and sea.

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