Future proofing New Zealand’s shellfish aquaculture: monitoring and adaptation to ocean acidification

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8.4 Levels of measurement: effort and costs 17
8.5 Hales’ approach to continuous measurement of TCO₂ and pCO₂ 18
8.6 Take-home messages for determining Ω 18
9 Ocean acidification in New Zealand 18
  9.1 Existing, ongoing monitoring programs 18
  9.2 Potential sites for coastal acidification monitoring in New Zealand 19
  9.3 Global Ocean Acidification Observing Network (GOA-ON) 20
10 Shellfish aquaculture in New Zealand 21
  10.1 Revenue and production 21
  10.2 Harvest of spat for Greenshell mussel and Pacific oyster 21
  10.3 Sites of Greenshell mussel and Pacific oyster production 22
  10.4 Declines in Greenshell mussel production 23
  10.5 Industry questions for science 24
  10.6 Learning and adapting 25
  10.7 Finfish aquaculture, Chinook salmon and wild fisheries 25
11 Greenshell mussel (Perna canaliculus) vulnerability to ocean acidification 25
  11.1 Potential vulnerabilities P. canaliculus veliger larvae to ocean acidification 26
  11.2 The impacts of variable pH on early P. canaliculus veliger larvae 26
  11.3 Preliminary conclusions 26
  11.4 Looking forward: Priorities for understanding the implications of ocean acidification on P. canaliculus production 27
12 Ocean acidification impacts on New Zealand abalone, cockle, and flat oyster 28
  12.1 Shell carbonate mineralogy varies between organisms 28
  12.2 Experiments conducted on juvenile phases of the cockle, abalone, and flat oyster to assess the impacts of variable pH and/or temperature 28
  12.3 Conclusions 28
  12.4 Future work 29
13 Ecosystem impacts of Ocean acidification: New Zealand perspectives 29
  13.1 Impact of ocean acidification on bacterial degradation of organic matter 29
  13.2 Are nitrogen fixers potential “winners” under ocean acidification? 29
  13.3 Coastal macroalgae communities under declining pH 30
  13.4 Relationship between cold water coral distribution and aragonite saturation horizon (ASH) 30
  13.5 Impact of ocean acidification on echinoderm larvae 30
14 Linking ocean acidification, eutrophication, and land use 30
  14.1 How is NEM linked with acidification and eutrophication? 31
  14.2 Assessment of NEM in the Hauraki Gulf and Firth of Thames 31
  14.3 Long term monitoring program in the Firth of Thames 32
  14.4 Conclusions 32
  14.5 Next steps 32
EXECUTIVE SUMMARY


1. Nearly a third of atmospheric carbon dioxide (CO₂) dissolves in the oceans; this has driven a progressive increase in ocean acidity (decline in pH) since the start of the industrial revolution.

2. Increasing levels of CO₂ in our oceans affects the formation of calcium carbonate shells and skeletons, potentially influencing growth and, ultimately, threatening an organism’s survival. Molluscs have been shown to be vulnerable, particularly during larval stages.

3. Research conducted by scientists from Oregon State University, in collaboration with the shellfish industry and the U.S. National Oceanic and Atmospheric Administration, was able to establish a causal link between dramatic declines in production at U.S. Pacific Northwest shellfish hatcheries and increasing ocean acidification during upwelling events from 2007 onwards.

4. The water’s suitability for CaCO₃ formation is determined by the saturation state (represented by the Greek letter omega, Ω). As Ω goes down, shell growth becomes increasingly difficult, ultimately threatening an organism’s survival. One form of CaCO₃, aragonite, is particularly vulnerable to increasing acidity (declining pH) and represents a key component of mollusc shells, particularly during vulnerable larval stages.

5. Subsequent work has determined that it is the hatchery water’s aragonite saturation state (ΩAr), particularly during the first two days of life, which predominantly influences the fate of oyster larvae and net production. Innovative hardware developed by Burke Hales of OSU, capable of making measurements that allow the calculation of ΩAr in real-time, has been indispensable for routine hatchery management.

6. Pacific Northwest hatcheries operated by Whiskey Creek Shellfish Hatchery and Taylor Shellfish Farms have successfully recovered most of their production by implementing dynamic procedures to avoid seawater with unfavourable ΩAr levels. Avoidance measures include not filling tanks with water for rearing shellfish larvae when ΩAr falls below critical levels. Mitigation includes the chemical treatment of hatchery water to increase ΩAr.

7. Seawater analysed in the on-going Munida Time Series monitoring off the coast of Otago, southern New Zealand, shows that the open ocean waters off New Zealand are acidifying at rates comparable to average global trends. Corresponding lab simulations suggest that some of New Zealand’s key coastal shellfish species may be vulnerable to future predicted levels of ocean acidification.

8. Ocean acidification will impact a range of marine species, food webs, and marine ecosystems. For example, scientists have estimated that by 2100, less than 25% of existing coral locations in New Zealand will be able to sustain coral growth.

9. New Zealand shellfish growers have now engaged with New Zealand researchers and their U.S. counterparts and are actively seeking ways to enhance plans for a coastal ocean acidification monitoring network in New Zealand, as well the potential for continuous assessment of ΩAr in commercial hatcheries.
10. The momentum and good will created by this workshop has provided a platform for on-going communication and collaboration in this exciting new area of science and industry cooperation.

11. Collaborating with scientists, policy makers, and marine farmers from other countries creates opportunities for technology transfer and knowledge exchange, and will be an ongoing component in New Zealand’s attempts to improve the resilience of the shellfish and aquaculture industries to future changes in ocean chemistry.
1 INTRODUCTION

Report from the New Zealand-U.S. workshop, Nelson New Zealand, 3-4 December, 2013

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“Ocean acidification is a very important subject for the maintenance of our beautiful treasures, of our oceans, of our waterways.”
Archdeacon Harvey Ruru, New Zealand

“These changes affect us now; our trade, our climate, and the security of our food sources - it’s not a future problem, it’s a problem now.”
Marie Damour, Deputy Chief of Mission, U.S. Embassy Wellington, New Zealand

“The only way we’re going to stop acidification is to get out in front on this issue - nobody else is going to do it, and we’re the guys who will first go out of business. So I encourage you to get on board with this issue, convince yourself first, and get out there and convince other people before it’s too late.”
Alan Barton, Whisky Creek Shellfish Hatchery

“Over the last year, in both Kaitaia and Golden Bay, we have had real problems with mussel retention: so why is that, is it food, is it ocean acidification? We haven’t got a clue. We’ve just got problems. And that’s one of the major impacts of running a mussel business in New Zealand. We don’t catch a lot of spat in Marlborough Sound right now and we don’t know why.”
Ted Culley, Sanford Limited

“It is crucial that scientists and industry articulate their concerns clearly to government, particularly given the surge in political interest in the marine economy.”
Mary Livingston, Principal Scientist Aquatic Environment, MPI.

1.1 Purpose of workshop

The workshop, Future proofing New Zealand’s shellfish aquaculture: Monitoring and adaptation to ocean acidification, was held on December 3rd and 4th, 2013, in Nelson, New Zealand and brought together more than 60 experts from government, the shellfish aquaculture industry, and science organizations from the United States of America and New Zealand. The overarching goals of the workshop were to raise awareness of ocean acidification within the New Zealand shellfish aquaculture community, identify ways to protect New Zealand’s NZD $375M per year aquaculture industry from ocean acidification, strengthen New Zealand’s existing efforts to monitor ocean acidification and assess its impacts, and further develop U.S.-New Zealand scientific cooperation to address ocean acidification. This report summarises the papers presented at the workshop and attempts to capture the key points raised during workshop discussions.
1.2 Background

Ocean acidification (OA) is recognized as a global threat to the shellfish aquaculture industry because many farmed species are sensitive to changes in carbonate chemistry, a consequence of OA, which is increasing at unprecedented rates. OA is caused by increasing carbon dioxide (CO₂) in seawater, which combines with other elements, such as fresh water runoff and agricultural effluents, to create conditions that can be corrosive to commercially and ecologically important species. Organisms with calcium carbonate shells or skeletons including corals; shellfish such as oysters, scallops and mussels; and many other species are threatened by increasing OA.

The Ocean Acidification Workshop aimed to bring together scientific experts and industry representatives from the U.S. and New Zealand to discuss how U.S. industry and scientists have partnered to address the impacts of OA on shellfish production in the U.S., and to identify the steps that can be taken to reduce the current and future risks to New Zealand’s shellfish industry. It was envisaged as an opportunity for the U.S. to transfer technology and build international partnerships for OA monitoring. In turn, improvement in the capacity to monitor OA in New Zealand will provide a platform for other countries in the region to benefit from scientific capacity building and technology transfer.

The workshop was also identified as a significant step towards meeting MPI’s Aquaculture Unit Five Year Strategy, released in 2012 which has an objective to “Increase Value through Research and Innovation.” Under this objective sits the action, “Investigate the impacts of climate change and measures to adapt and respond”.

INTRODUCTION TO OCEAN ACIDIFICATION

The issue: Atmospheric CO\(_2\) levels are rising as a result of human activities, such as the burning of fossil fuels, and are increasing the acidity of seawater, a process known as ocean acidification. Historically, the ocean has absorbed approximately 30% of all CO\(_2\) released into the atmosphere by humans since the start of the industrial revolution (Riebesell 2010; IGBP et al. 2013).

The chemical changes in seawater resulting from increased atmospheric CO\(_2\) concentrations include increases in the concentrations of dissolved (or aqueous) CO\(_2\), hydrogen ions (H\(^+\)), and bicarbonate ions (HCO\(_3^-\)), and decreases in the carbonate ion (CO\(_3^{2-}\)) concentration making the formation of calcium carbonate (CaCO\(_3\)) less favourable, effectively making it more difficult for organisms with calcareous structures, e.g., corals, pteropods, and early life stages of larval shellfish, to build calcium carbonate shells (Figure 1).

Since the Industrial Revolution, open ocean pH has dropped on average by about 0.1 pH units (a 26% increase in [H\(^+\)]) , and additional declines of between 0.2 and 0.3 pH units will occur over the 21st century unless human CO\(_2\) emissions are curtailed substantially (Doney 2010). In addition to the impacts of atmospheric CO\(_2\), the coastal zone is subject to natural and anthropogenic stressors that can exacerbate or mitigate ocean acidification effects (Waldbusser & Salisbury 2014).

**Useful indicators**: Figure 1 shows that the biochemistry of ocean pH is complex and it is difficult to identify what the key components are to use as indicators of when marine organisms are likely to be affected. To compare how easy or difficult it should be for organisms to build their CaCO\(_3\) shells and skeletons in waters with different chemistries, scientists use CaCO\(_3\) saturation states, represented by the symbol omega (Ω). As a general rule, the following relationships apply, although they must be considered in the context of the particular organisms as sensitivity to Ω can vary by species and life stage.

- At Ω > 1, CaCO\(_3\) is thermodynamically stable (no dissolution)
- At Ω < 1, CaCO\(_3\) shell dissolves
- At Ω >> 1, it is easier for an animal to build and maintain a shell
There are two main forms of calcium carbonate used for shell and skeleton building, calcite and aragonite, whose saturation states are referred to as $\Omega_{Ca}$ and $\Omega_{Ar}$, respectively. Aragonite, in particular, plays an important role in the calcareous structures produced by corals, pteropods, and early life stages of larval oysters (Stenzel 1964, Barton et al. 2012).

From the perspective of an organism that requires CaCO$_3$, any decrease in $\Omega$ is potentially negative as it requires that more energy is diverted to building shell at the expense of other key processes (e.g., building a velum necessary for feeding). For example, many species of shallow water corals exhibit worrisome decreases in calcification when $\Omega_{Ar}$ remains significantly higher than 1. The majority of the world’s shallow water coral reef species evolved in waters with $\Omega_{Ar}$ greater than 4 and tropical reefs are expected to become marginal at best (compromised) when $\Omega_{Ar}$ is about 3–3.5, which is projected for most coral reefs by the middle of this century (Guinotte & Fabry 2008). This example shows that biological responses to ocean acidification may begin well before $\Omega_{Ar}$ reaches 1. The response of different species and even life stages of those species to reductions in $\Omega$ vary.

3 THE IMPORTANCE OF $\Omega_{AR}$ FOR THE PACIFIC OYSTER (CRASSOSTREA GIGAS) AND MUSSELS (MYTILUS SPECIES.)

(Summary of presentations by George Waldbusser and Burke Hales)

In experiments with Pacific oysters and Mediterranean mussel larvae, water chemistry was manipulated to test the sensitivity of shellfish larvae to the different parameters of the CO$_2$ system. At constant $\Omega_{Ar}$, varying pH from 7.43–8.88 and pCO$_2$ from 400–2800 ppm showed no evident impact on larval development. In contrast, the data revealed a clear correlation between values of $\Omega_{Ar}$ and normal larval development. Figure 2 shows that at similar pCO$_2$ values (2a–2b and 2c–2d) but variable $\Omega_{Ar}$, there is a difference between shell degradation that is correlated with $\Omega_{Ar}$. Also noteworthy is the appearance of a healthy shell even at a pCO$_2$ value of 2758 ppm (Fig. 2d). This underscores the importance of monitoring $\Omega_{Ar}$ as it appears to be the critical carbonate system parameter for these species.

![Figure 2: Scanning electron micrographs of D hinge M. galloprovencialis exposed at variable levels of pCO$_2$ (ppm) and values of $\Omega_{Ar}$. 3a and 3c show shell degradation corresponding to low $\Omega_{Ar}$.](image-url)
4 OCEAN ACIDIFICATION IN THE U.S. PACIFIC NORTHWEST

4.1 Chemical oceanography

(Summary of presentation by Burke Hales)

The central and southern coastal region off western North America is strongly influenced by seasonal upwelling. Northwesterly winds drive net surface-water Ekman transport offshore, which induces the upwelling of CO₂-rich, intermediate-depth offshore waters onto the continental shelf. The upwelled water off northern California was last at the surface about 50 years ago, when atmospheric CO₂ was about 80 ppm lower than it is today. It is estimated that 10% of the CO₂ contained in these waters are from anthropogenic sources (Feely et al. 2008). A recent modelling study for the California Current System projected that by 2050, waters with $\Omega_A$ above 1.5 will have largely disappeared, and more than half of the waters will be undersaturated year-round (Gruber et al. 2012). There are nutrients as well in the upwelled water including nitrates, phosphates, and silicates, that fuel phytoplankton blooms that are retained on the shelf and die, consuming oxygen and producing CO₂, amplifying the signals of upwelling and the human impacts of ocean acidification in shelf and nearshore waters. Hypoxia and acidification may be linked, but the relationship between the two is not yet clear.

4.2 The shellfish industry in the U.S. Pacific Northwest

(Summary of presentations by Bill Dewey and Alan Barton)

Shellfish farms are found in Alaska, Washington, Oregon, and California where the major shellfish species are Pacific oysters, geoduck clams ($Panopea$ $generosa$), Manila clams ($Venerupis$ $philippinarum$), and blue mussels ($Mytilus$ $edulis$). Manila clams and Pacific oysters are non-native species. The Pacific oyster is accustomed to a warmer climate and even where it is established it does not reproduce dependably every year. Accordingly, the commercial oyster industry is dependent upon hatcheries that produce eyed oyster larvae (pediveliger) which are distributed to shellfish growers and out-planted to estuaries for their adult lives. The production of Pacific oyster larvae is the bottleneck for the shellfish aquaculture industry in the U.S.

4.3 Impacts of ocean acidification on oyster larvae in the U.S. Pacific Northwest

(Summary of presentations by Bill Dewey and Alan Barton)

Dewey indicated that the ocean acidification problem in Washington state first emerged in 2005 and 2006 (Welch 2009). In some areas, natural ‘sets’ (i.e., where planktonic, free-swimming, oyster larvae metamorphose to the benthic adult form) began to fail. In Oregon, the Whiskey Creek Shellfish Hatchery located in Netarts Bay and which produces 10 billion eyed larvae each year, experienced mortalities of up to 80% starting in 2007 and 2008. The populations of $Vibrio$ $tubishii$, a bacterium that is a pathogen of oyster larvae reached unprecedented levels in the bay. In response, Barton and colleagues installed a sophisticated system of filters to remove the bacteria, but the larvae kept dying suggesting that $Vibrio$ was not the primary cause of larval mortality.

A partnership between the staff of the Whiskey Creek Shellfish Hatchery, scientists from the National Oceanic and Atmospheric Administration (NOAA), Hales, and Waldbusser established the link between highly variable carbonate chemistry and oyster larvae die-offs (Barton et al. 2012). When the CO₂-rich water washes into Netarts Bay and is pumped into the oyster larvae tanks, the excess CO₂ causes the seawater’s acidity to spike, lowering $\Omega_A$ and making it more difficult for larvae to build CaCO₃ shells.

The Whiskey Creek Shellfish Hatchery proved to be an ideal field laboratory for assessing the impacts of carbonate chemistry on the development and survival of oyster larvae. Carbonate chemistry conditions in the hatchery are set by Netarts Bay but temperature and food availability are controlled by the hatchery. The work demonstrated early larval sensitivity to ocean acidification. Barton
indicates that at the supposed ‘break even’ point for larval survival of $\Omega_{Ar} = 1.7$, which corresponds to 70% survival, the hatchery loses money. It is important to note that $\Omega_{Ar} = 1.7$ is well above the saturation value of $\Omega_{Ar} = 1$, the point at which aragonite is thermodynamically stable. The response of wild oyster populations to changes in carbonate chemistry is not well known.

4.4 Industry response in Oregon and Washington

(Summary of presentation by Alan Barton)

As summarized in Section 8.5, hatcheries in both Oregon and Washington have implemented a rigorous system of continuous monitoring of seawater at their hatchery intakes that provides values of $\Omega_{Ar}$ in real time and allows growers to fill tanks for growing larvae when conditions are optimal (Figure 3). Conditions for filling tanks are optimal ($\Omega_{Ar}$ over 2.0) for less than 10% of the time, which means that seawater treatment is required year-round.

![Figure 3: Optimal (green) and suboptimal (salmon) times for filling hatchery tanks for the growth of C. gigas. Wind direction and intensity (a), salinity (b), performance of small larvae (c), and $\Omega_{Ar}$ (d).](image)

4.4.1 Public relations

(Summary of presentation by Bill Dewey)

Dewey and Barton devote considerable time and effort to media, documentary production and speaking at various local, state, federal and international forums on ocean acidification and are often featured in the popular and scientific press (e.g. Service 2012). Taylor Shellfish Farms has two full-time staff giving presentations in classrooms and conducting tours of their shellfish farms. In 2011 and 2012 Taylor’s Outreach & Education Coordinators conducted 438 classroom visits and presentations and 202 field trips and tours. They have directly reached an estimated 16 000 people.
through presentations that address shellfish farming, water quality, ecosystem services, and ocean acidification. These outreach programs have been great public relations tools for the business and have had a beneficial impact on their relationship with the State government, e.g., making it easier to obtain permits for shellfish farming.

4.4.2 Increased capacity and relocation to produce more larvae

Taylor shellfish Farms has increased the capacity at their shellfish hatchery in Dabob Bay in order to compensate for the decreased production of oyster larvae. They have introduced flow-through tanks in their hatcheries which can accommodate greater densities of shellfish larvae. Taylor also has a hatchery in Kona, Hawaii that has been a valuable resource in light of increasingly acidified waters in the Pacific Northwest.

4.5 Policy to address ocean acidification in Washington State

(Summary of presentation by Bill Dewey)

After hatcheries in Oregon and Washington determined that acidified seawater was responsible for the mortality of shellfish larvae, they enlisted the help of Senator Maria Cantwell to secure USD $500 000 in 2010 from the U.S. government’s economic stimulus program. The hatcheries worked in partnership with Hales and others to set up a network of detectors to closely monitor carbonate parameters, temperature, salinity, and dissolved oxygen levels in Netarts Bay and two other prominent oyster-rearing grounds in Washington.

Washington Governors Gregoire (2005–13) and Inslee (current) have been responsive to the needs of the shellfish industry. In 2011, NOAA released a National Aquaculture Policy that included a National Shellfish Initiative. Guided by that national effort, Governor Gregoire of Washington State launched a State-level initiative. Among the activities included in that statewide initiative was the formation of an Ocean Acidification Blue Ribbon Panel which was tasked with providing guidance on dealing with ocean acidification, a panel on which Dewey served and which included policy makers, scientists, legislators, industry, native American tribes, and environmental groups. There are 42 recommendations and a scientific appendix (Washington State 2014a).

Highlights of the Washington State Blue Ribbon Panel include the following actions:

- Reduce emissions of carbon dioxide.
- Reduce local land-based contributions to ocean acidification.
- Increase the ability to adapt and remediate impacts of ocean acidification.
- Invest in Washington State’s ability to monitor and investigate the causes and effects of ocean acidification.
- Inform, educate and engage stakeholders, the public and decision makers on ocean acidification.
- Maintain a sustainable and coordinated focus on ocean acidification at all levels of government.

The governor of Washington passed an Executive Order in 2012 to implement the 42 recommendations. Of the USD $3.3M requested, $1.8M were appropriated. The State legislature passed a Senate Bill 5603 in 2013 which created a Washington Marine Resources Advisory Council in the Governor’s office that will continue the work of the Blue Ribbon panel (Washington State 2014b). Part of the $1.8M was used to create an ocean acidification center at the University of Washington. Among the priority areas of the center are: (i) water quality monitoring at the six existing shellfish hatcheries and rearing areas and; (ii) an expanded and sustained ocean acidification monitoring network (UW 2014).
5 OCEAN ACIDIFICATION AND SHELLFISH HATCHERIES IN THE GULF OF MAINE

(Summary of presentation by Bill Mook)

Mook Sea Farm is located in middle of coastal Maine and supplies post set juveniles of the native species, the eastern oyster (Crassotrea virginica), to other growers on the U.S. East Coast, and market-sized oysters to the domestic half shell market. Mook Sea Farm employs 9 people and produces 80 to 100 million juvenile oysters each year.

On the East Coast of the U.S., oceanographers have discovered that the waters of the Gulf of Maine are particularly vulnerable to ocean acidification. The geology is granitic which means that freshwater runoff from the surrounding land has low buffering capacity. Relatively fresh, cold water from the Labrador Current exacerbates the impacts of ocean acidification for shell-building organisms and other marine life.

5.1 Causes for concern

While Mook Sea Farm is running well and is profitable, there are several reasons for concern:

i. The impacts of ocean acidification on shellfish hatcheries on the U.S. West Coast were a “wake up call” in light of their potential impacts on the business.

ii. From 2007–2010, there was a dramatic decrease in the frequency and intensity of phytoplankton blooms in the Gulf of Maine. This coincided with the observation in 2009 of extreme difficulty growing certain strains of algae, including Isochrysis which is cultivated as a staple food for oyster larvae.

iii. An increase in the number of extreme rainfall events over the past decade in the Gulf of Maine and subsequent freshwater runoff events have coincided with reduced larval feeding and growth rates, but there is no evidence of a link between them at this stage.

5.2 Impacts on phytoplankton

Two hypotheses are considered for point ii: First, record or near-record precipitation over the past decade is coincident with five-fold declines in the production of phytoplankton in the Gulf of Maine which form the foundation of the marine food webs that support the gulf’s fish and lobster populations (Balch et al. 2012). The second hypothesis is that the rain is bringing metals into the water which are toxic to phytoplankton.

5.3 Impacts on oyster larvae

Reduced swimming of oyster larvae and swarming at the bottom of the tank has been observed since 2009 and is correlated with measurements of pH 7.9 or less. Mook Sea Farm is working with researchers from the University of New Hampshire to install sensors in both the incoming seawater and larval tanks in order to determine Ω Ar. Mook anticipates that the improved monitoring of the water chemistry associated with each larval spawn will illuminate the reasons behind reduced larval feeding and growth.
6 IMPACTS OF OCEAN ACIDIFICATION ON THE PACIFIC OYSTER, THE HARD CLAM, AND THE SOFT-SHELL CLAM

(Summary of presentation by George Waldbusser)

6.1 Manifestation of ocean acidification impacts in C. gigas

The results shown in Figure 4 demonstrate that the impacts of low values of Ω_{Ar} during the first 48 hours post fertilization may not be immediately evident but are manifest later, in this case, the stage at which larvae are commercially valuable. Initial survival (4a) early growth (4b), and mid-growth (4c), show little if any correlation with the values of Ω_{Ar} during the first 48 hours following fertilization, but total production of the seed oyster (4d), at which stage larvae are commercially viable, shows a linear correlation with Ω_{Ar} during this crucial period (Barton et al. 2012).

![Figure 4: Over 50% of the hatchery production is explained by values of Ω_{Ar} during the first 48 hours post fertilization. Relationship between Ω_{Ar} and (a) proportion of larvae developing to D-hinge stage, (b) number of days for larvae to reach a nominal 120-μm size, (c) number of days for larvae to grow from 120- to 150-μm nominal size, and (d) overall relative production of each larval cohort. Each dot is an individual cohort of larvae. Data points in black on graphs 5c and 5d are statistical outliers and were excluded from regression analysis. Harvested fertilized eggs were exposed to waters with variable values of Ω_{Ar} for 48h (from Barton et al. 2012).](image)

6.2 The energetics of shell formation

Following fertilization, oyster larvae go from a state of having virtually no mineral to a fully mineralized shell in a 3–5 hour window following the trochophore stage (Figure 5). Within 48 hours oyster larvae become approximately 80–90% calcium carbonate by weight. The time window is short since the larva cannot begin feeding until it has built its velum (the swimming and feeding appendage). The building of the first shell and the feeding mechanism is all accomplished with maternal energy from the egg, a discrete larval ‘lunch bag’. Suboptimal values of Ω_{Ar}, even when over 1, mean that larvae must expend more energy before it can feed itself. If the “lunch bag” is depleted before the shell and feeding mechanism are in place, it will die.
Waldbusser described the use of $^{13}$C isotopes to study larval development. These experiments demonstrated the transition from endogenous energy sources derived from egg reserves to exogenous food sources for developing bivalve larvae during the first two weeks following fertilization. Calcification is biologically mediated and requires energy. Waldbusser and Hales propose that the kinetics of shell formation obey the equation:

$$r = k \left( \Omega_{Ar} - 1 \right)^n$$

Where $r =$ calcification rate, $k =$ rate constant and $n =$ reaction order. This hypothesis assumes that the larvae must overcome a kinetic constraint and do so by altering $k$ or $\Omega_{Ar}$ (Waldbusser et al. 2013).

### 6.3 Impacts of ocean acidification on the hard clam, *Mercenaria mercenaria*

There is very little information on early juvenile ecology of the hard clam, and what a settling larva experiences is likely to be very different from the conditions in the overlying water. Fewer than 20% of hard clam larvae survived to fully metamorphose into juvenile clams at $\Omega_{Ar}$ values of 1.92, compared to 76% survival at $\Omega_{Ar}$ levels of 2.37. Importantly, these impacts were manifest primarily when undergoing metamorphosis from the pediveliger to juvenile clams (Talmage & Gobler 2009).

Figure 6 shows that mortality is a function of both larval size and $\Omega_{Ar}$. For example, when 0.2 mm *M. mercenaria* were reared in sediments at $\Omega_{Ar} =$ 0.4, the mortality of individuals was 14% compared to 3.9% at $\Omega_{Ar} =$ 1.4. Post-larvae settle to sediments and grow rapidly, allowing juveniles to escape predation pressure and possibly acidification stress. The values of $\Omega_{Ar}$ had no significant impact on the survival of 2.0 mm larvae. Coastal deposits that are undersaturated with respect to calcium carbonate represent normal geochemical conditions for these surface deposits (Green et al. 2009).
Waldbusser has developed a model to synthesize the experimental data and suggests that larvae can overcome undersaturation (i.e., calcify when conditions are corrosive) when they are about 1 mm in length, at which size they are at dissoconch II stage and have developed the inhalant and inner folds of a manifold and can capture food. The outcomes of these experiments suggest a potential breeding strategy for overcoming increasingly acidified coastal environments, as faster growing shellfish larvae have higher survival rates.

6.4 Using crushed shell to increase survivorship of the soft-shell clam (Mya arenaria)

Mark Green and colleagues studied the impact on bivalve recruitment of raising the aragonite saturation state of surface sediments by buffering with crushed shell. In experiments with the soft-shell clam, they increased the average sediment saturation state from $\Omega_{Ar} = 0.25$ to $\Omega_{Ar} = 0.53$, and found that the number of live $M. arenaria$ in buffered sediment increased almost three-fold (Green et al. 2009). These findings were confirmed with laboratory experiments in which $\Omega_{Ar}$ was altered without the use of shell to alleviate some of the other effects of shell material on settlement behaviour.

7 IMPACTS OF OCEAN ACIDIFICATION AND TEMPERATURE ON BYSSAL THREADS IN THE PACIFIC MUSSEL (MYTILUS TROSSULUS)

(Summary of presentation by Emily Carrington)

7.1 Byssal thread structure

Byssal threads (Figure 7) are extracellular, non-living fibres made by the mussel’s foot, 50–200 of which anchor the mussel to the substrate. The strength of a mussel’s byssal attachment (made of many threads) is measured by its tenacity, as measured by the equation:

\[
\text{Tenacity} = \frac{\text{Force to dislodge (Newtons)}}{\text{Shell area (m}^2)}
\]

Up to 20% of the mussel harvest may be lost due to weak attachment, which could mirror natural populations in which one third may become unattached each year. Dislodgment is a natural phenomenon but the question is whether it is possible to predict its timing and severity.

![Figure 7: Regions of a byssal thread. Normal byssal threads are strong, and extensible, yield in distal region, and fail in proximal region or plaque.](image)

7.2 Byssal attachment strength varies seasonally

It was shown that byssus material properties vary seasonally: In the boreal spring, they are strong and extensible, while in the fall they are weak and inextensible (Moeser & Carrington 2006). In the state of Rhode Island, mussel dislodgment is concentrated in September and October when increased storm intensity coincides with weak attachment. Storms arriving later in the winter and spring, when attachment is stronger, do not dislodge mussels.
The reasons for this variation in mussel attachment are unknown but there are a suite of potential mechanisms that could account for weaker attachment: (i) lower thread production; (ii) inferior thread quality; and (iii) faster thread decay. The factor that appears to dominate weak attachment in Rhode Island is inferior thread quality.

### 7.3 Why are mussels weak?

What is driving the weak mussel attachment in the Rhode Island summertime is unknown but the suite of interrelated potential environmental and physiological factors include (Moeser & Carrington, 2006):

- poor physical condition (low meat weight of mussel)
- poor reproductive condition, having just spawned
- warm water, up to 25°C
- low food supply due to a stable thermocline which precludes mixing
- high parasite prevalence.

### 7.4 Impacts of high pCO₂ on byssal thread tenacity

In experiments that examined the impacts of high pCO₂ on byssal threads, it was shown that threads become weaker and less extensible, causing mussels to lose 40% of their tenacity (Figure 8) (O’Donnell et al. 2013). As pCO₂ is increased from 300–1500 μatm there is a bias towards failure in the plaque region. Threads are less extensible and do not yield in the distal region.

![Figure 8: Individual byssal threads become weaker and less extensible in a high pCO₂ environment, collectively leading to 40% less whole animal tenacity over the range of pCO₂ values examined.](image)

### 7.5 Impacts of variable temperature on byssal thread tenacity

The effects of elevated temperature on byssal threads was also examined. It was found that at high temperatures, threads fail in the proximal region, are 60% weaker, and are less extensible (Figure 9).
7.6 The combined effects of variable pH and temperature

The effects of variable pH and temperature were varied simultaneously in order to assess the impact of multiple stressors. It was found that the impact of high temperature dominates byssal thread failure, masking the effect of pH. At more benign temperatures, the pH effect is measurable (Figure 10).

7.7 How can we promote increased tenacity (retention)?

- Add horizontal structure to culture rope, e.g., mussel discs provide extra structure to keep mussels from sliding down the rope.
- Keep stocking density low. If mussels are in layers, then mussels on the outside may do better than those inside, which may be related to food supply or chemistry.
- Reduce sedimentation, e.g., by not hanging the rope too low or avoiding silted waters.
- Selective breeding for mussels that have better attachment.

7.8 What are the data gaps?

- The absence of data that correlates the weakening of byssal threads and environmental conditions.
- The lack of understanding of the micro-environment in which mussels make the byssal threads, an environment about which we know essentially nothing.
8 CARBONATE CHEMISTRY MEASUREMENTS

(Summary of presentation by Burke Hales)

8.1 Problems associated with measuring pH

Of the four carbonate parameters, pH is the easiest to measure but also easiest to measure incorrectly. Many of today’s pH sensors cannot accurately measure the difference between contemporary pH levels and the pH before the beginning of the industrial revolution. In addition, the window of pH values of relevance to shellfish aquaculture is narrow, encompassing a range of pH 7.5–8.2. Although skilled analysts can produce useful data, the challenges associated with measuring pH include that pH is:

1. Easy to observe but difficult to interpret
2. Prone to sensor noise that is larger than environmental signals
3. Subject to environmental biases (such as variable salinity)
4. Rarely a driver of biological responses
5. An imperfect indicator of conditions relevant to shellfish
6. Measurable using multiple pH scales
7. Prone to sensor instability
8. Not conservative with respect to temperature, salinity, and pressure, e.g., a sample measured in the field will yield different results in the laboratory
9. Difficult to compare because of the lack of suitable standards for calibration of pH sensors in estuarine settings

8.2 Constraining the carbonate system

Full constraint of the carbonate system is required for the accurate calculation of $\Omega_{Ar}$, including the following requirements (Riebesell et al. 2010):

- Temperature and salinity measured with an error of no greater than 0.1.
- Use of the appropriate thermodynamic constants (e.g. Millero & DiTrolio 2010, Mucci 1983).
- Measurement of any two of following carbonate system parameters: pH, partial pressure of CO$_2$ (pCO$_2$), total CO$_2$ (TCO$_2$, also known as dissolved inorganic carbon [DIC]), total alkalinity (TA), at near state-of-the-art accuracy and precision.
- Use of a suitable seawater carbon calculator (e.g., CO2Calc).

8.3 An assessment of measurable carbonate parameters

pH: Inexpensive, and real-time sensing is possible; however has issues with scale definitions, uncertain temperature (T) and salinity (S) dependencies, sensor instability, not being conservative with respect to T, S, and Pressure (P), and requires a skilled user.

pCO$_2$: A well-defined parameter, possibly of direct interest, free from scale-definition uncertainty, and real-time sensing is possible, with high signal-noise; however it is expensive, and not conservative with respect to T, S, P, and requires a skilled user.

TCO$_2$ (Total CO$_2$, also referred to as DIC, CT, and $\Sigma$CO2): A well-defined parameter free from scale-definition uncertainty, with real-time sensing possible, and conservative with respect to T, S, P; however it is expensive and requires a skilled user.

TA: (Total alkalinity): Inexpensive, approximately conservative with respect to T, S, P; however accuracy is difficult to achieve, it has a complicated definition that may depend on specific characteristics of any local freshwater input, requires time-intensive analysis and a skilled user. Alkalinity can also be difficult to define in an estuarine system.
The best approach to determine $\Omega_{Ar}$ is through measurement of one of the ‘high-signal’ parameters, pH or pCO$_2$ (pCO$_2$ preferable to pH), and T, S continuously, at high-frequency, along with one of the ‘conservative’ parameters TA or TCO$_2$ (TCO$_2$ preferable to TA) at lower frequency.

Figure 11 shows that other directly-measurable parameters alone are poor $\Omega_{Ar}$-predictors. At pH 8, even when measured during the same year, values of $\Omega_{Ar}$ ranged from 0.7 to 1.5 for the same value of pH (left). The same phenomenon is observed for pCO$_2$ (right).

8.4 Levels of measurement: effort and costs

In order of increasing complexity, effort, and costs:
- Discrete samples collected at the user’s discretion, analysed for the preferred parameter pair; at a cost of USD $20-200/sample. This is a good way to get started. Discrete samples allow continuous data of moderate quality to be useful (Fig. 13).
- Choice of one continuously-measured parameter, plus discrete samples for validation and pseudo-constraint of system.
- Two continuously-measured parameters, e.g., pCO$_2$ and pH, or preferably, pCO$_2$ and TCO$_2$ (Figure 12)

Figure 12: Even pH data of low resolution can be validated with discrete samples of other carbonate parameters. Values of pH from the corrected in situ measurements made with a YSI sonde at the hatchery intake (blue line) and calculated from the discrete samples analysed for PCO$_2$ and TCO$_2$ (blue circles), Aragonite saturation state calculated from the corrected YSI pH data (green line) and from the discrete measurements of PCO$_2$ and TCO$_2$ (green circles) (Barton et al. 2012; Copyright (2012) by the Association for the Sciences of Limnology and Oceanography, Inc.).
8.5 Hales’ approach to continuous measurement of TCO$_2$ and pCO$_2$

- TCO$_2$: Continuous IR-absorption analysis of a gas stream stripping an acidified flowing sample stream
- pCO$_2$: Continuous IR-absorption analysis of gas stream equilibrated with a flowing sample stream

Measurements of pCO$_2$ and TCO$_2$ is accomplished with the same detector using a system developed by Hales known within the U.S. shellfish aquaculture community as the “Burke-O-Lator” (Figure 13). Measurements can be made on a ship- or land-based system that has a continuous source of seawater allowing continuous measurement of pCO$_2$ and near-continuous measurement of TCO$_2$.

8.6 Take-home messages for determining $\Omega$

- Doing it right is expensive. The minimum approach is a laboratory pH system that costs about USD $5000, before integration into a broader data collection/processing interface, plus discrete bottle samples that can cost upwards of USD $100/per sample.
- No matter the approach, technical support is necessary, an estimated two months per year of technician time per field site.
- Coastal field stations with access to a pumped seawater stream offer many benefits over autonomous moorings.
- There are ways to get near state-of-the-art measurements without adhering to the standards of the World Ocean Circulation Experiment (WOCE 2014).

9 OCEAN ACIDIFICATION IN NEW ZEALAND

(Summary of presentation by Kim Currie)

9.1 Existing, ongoing monitoring programs

The Munida time series off the Otago coast, established in 1998, is the longest running carbonate chemistry time series in the Southern Hemisphere and includes coastal, modified subtropical and sub-
Antarctic surface waters (SASW) (Currie et al. 2009). Measurements are made every two months at this site and include pH, pCO₂, TA, and DIC.

Ocean acidification relevant data available in the country are also being, or have been, collected in the short-term at the following areas:

- Wellington Harbour (NIWA Mahanga Bay facility) (pH), frequency of past measurements have been sporadic, but continuous measurements will be collected beginning in late 2014.
- Karitane kelp bed (pH), one measurement.
- Marlborough Sounds (pCO₂), one measurement.
- Hauraki Gulf (pCO₂) (see Section 14.2), Seasonal surveys (four times per year) for 2013 and 2014. Continuous measurements currently being collected due to installation of new buoy sensor (August 2014).
- Chatham Rise moorings (TA, DIC), every six months for years 2009–2011.
- Ships of opportunity (pCO₂), NIWA RV Tangaroa has autonomous collection.

The SASW time series confirms that Southern Hemisphere surface waters are acidifying (Figure 14). The characteristics of this system include:

- A strong seasonal cycle driven by phytoplankton carbon uptake.
- A net decline in pH and carbonate ion saturation consistent with an increase in atmospheric CO₂.
- Changes in pH that are consistent with changes observed in other parts of the world.

![Figure 14: SASW time series showing changes in ΩAr (top) and pH (bottom).](image)

9.2 Potential sites for coastal acidification monitoring in New Zealand

Currie has suggested the development of a coastal sampling network in New Zealand. Potential monitoring sites (1–14) are shown in Figure 15 and are based on existing capacity, areas of high importance (i.e. aquaculture sites), and regions where little is known regarding carbonate chemistry.
The coastal sampling network would require measurement of TA and DIC with bottle samples which would be used to determine pH, carbonate, Ω Aragonite, in addition to measurements of temperature, and salinity. This network would take advantage of the central analytical facility at the NIWA/University of Otago Research Centre for Oceanography where carbonate chemistry can be determined with state-of-the-art instrumentation. One SeaFET solid state pH sensor has been purchased and three more SeaFETs will be purchased within the year for short-term deployment at the monitoring sites to determine short term variability.

9.3 Global Ocean Acidification Observing Network (GOA-ON)

The GOA-ON is a collaborative international approach to document the status and progress of ocean acidification in open-ocean, coastal, and estuarine environments, to understand the drivers and impacts of ocean acidification on marine ecosystems, and to provide spatially and temporally resolved biogeochemical data necessary to optimize modelling for ocean acidification (GOA-ON 2014). The data collected will address the scales of ‘weather’, namely the identification of relative spatial patterns and short term variation, and ‘climate’, namely to study long term trends, including any anthropogenically-driven changes. In New Zealand, no site currently meets GOA-ON criteria for weather or climate. Future plans call for upgrading the Munida time series and the Firth of Thames program to meet the climate criteria of the GOA-ON.
10 SHELLFISH AQUACULTURE IN NEW ZEALAND

(Summary of presentations by Ted Culley and Richard Ford)

10.1 Revenue and production

Revenue from mussels, oysters and salmon was in excess of NZD $300M in 2011 with shellfish representing the majority by volume (89%) and revenue (79% aquaculture export value). The average annual value of New Zealand shellfish aquaculture exports from 2008 to 2012 has been dominated by green-lipped mussels (*Perna canaliculus*) (NZ$197M) and Pacific oysters (*Crassostrea gigas*) (NZ$16M). When grown for aquaculture in New Zealand, *P. canaliculus* is produced under the trademark name “Greenshell”.

The Pacific oyster is an invasive species first recognized in New Zealand in 1971. Intertidal cultivation began in the mid 1970s and as of 2002 there were more than 200 farms in New Zealand covering almost 1000 hectares. Lesser known aquaculture species with smaller markets or under development include flat oysters, paua, geoduck, and sea cucumber. Flat oysters are a rising star in the aquaculture industry.

![Figure 16. Value of New Zealand aquaculture exports from 1989–2011.](image)

The demand for New Zealand shellfish aquaculture products is growing, a trend that is expected to continue (Figure 16). The global external drivers exist for an increasing demand if the product can be provided. Greenshell mussel for the U.S. market are at a record level, NZD $2.85/pound and rising, a 37% increase in price since March 2011 even though there has been a 15% decrease in volume. Sanford is currently the largest mussel farmer and processor in New Zealand, processing 31,500 tons in 2012. Sanford is keen to protect their significant investment in aquaculture sector and to future proof it from ocean acidification.

10.2 Harvest of spat for Greenshell mussel and Pacific oyster

In the case of Greenshell mussels, all seed stock is currently wild caught. The main sources are Ninety Mile Beach in Northland (Kaitaia) and Golden Bay at the top of the South Island (Figure 15). Eighty percent of the industry relies on spat from Kaitaia, the source of which is unknown. Much of the catchment in Golden Bay in the South Island goes to Marlborough Sounds.

Sanford has smaller spat catching areas such as Aotea harbour in the North Island and Banks Peninsula in the South Island. In order to help future proof the New Zealand mussel industry, the
Ministry for Primary Industries and Sanford Ltd. have invested NZD $26M in a commercial mussel hatchery venture (SPATnz) in Nelson, which will be operational by 2015.

Although the industry catches wild oyster spat in the Marlborough Sounds, and in the Northern parts of the North Island, and obtains spat from the hatchery in Nelson, animals may be grown in warm temperate/sub-tropical water in the north, mid-temperate waters in the Sounds, or cold temperate conditions at the southern end of New Zealand. The transfer of spat from a 20°C environment in the North, to a 10°C environment in Stewart Island, for example, creates challenges for retention.

10.3 Sites of Greenshell mussel and Pacific oyster production

Sanford Greenshell mussel production is focused on the Coromandel coast, the Tasman and Golden Bays, and the Marlborough Sounds (Figure 15). The vast majority of Sanford Pacific oysters are produced in the north of the country – Northland, Auckland and the Coromandel, with some production in the Marlborough Sounds. Sanford has a fledgling flat oyster operation in Marlborough and Stewart Island which in time may grow to be the third most significant shellfish species farmed in New Zealand (Figure 15).

Ford indicated that as of December, 2011, there were 23 279 hectares of allocated water space for marine-based aquaculture, approximately 56% nearshore, 38% considered open-ocean, and 6% undeveloped space in interim aquaculture marine areas (AMAs). It takes 10–12 years to get a site approved in New Zealand. The shellfish aquaculture industry went to offshore sites not because they are the best place to grow the animal, but because they are the easiest places to get permission to grow. Figure 17 shows aquaculture growing areas and estimated production (2012) for Greenshell mussels, Pacific oysters and salmon.
10.4 Declines in Greenshell mussel production

Sanford’s production has been impacted by poor conditions and slower growth in the North Island during the 2012 season and in the Marlborough Sound over the late 2012–2013 season. Conversely, product sourced from Canterbury and Stewart Island have performed beyond expectations with good growth and exceptional condition.

From the 12 months preceding September 2011, Sanford’s harvest was 98 922 mt, while for 2012 it was 90 177, and for 2013 it was 84 286 mt, representing a cumulative a drop of 15% since 2011.

Ford indicated that in the wild shellfish fisheries in the south, declines in green mussel landings and oyster catch have been attributed to multiple causes (Figure 18). NIWA is leading a qualitative modelling exercise to try and narrow down the lengthy list of possible reasons for these declines,
possible causes include: (i) shellfish disease; (ii) overfishing in some fisheries; and (iii) ocean acidification. For the moment ocean acidification is seen as a threat looming on the horizon rather than a likely cause of declining shellfish production. Improved monitoring is required to address the declines. Other confounding issues to be taken into account include: (i) climate change; (ii) nutrient enrichment from intensive agricultural practices (Zeldis 2008); (iii) sedimentation; and (iv) point source pollutants, which are a problem in isolated locations in New Zealand.

Ford cited ongoing research and development for Greenshell mussels including: (i) selective breeding; (ii) improved spat handling on Ninety Mile Beach for viability; (iii) mussel over-settlement (blue mussels growing on greenlip mussel lines; monoculture of greenlip mussels is preferred by industry); (iv) identifying the source of mussel spat; and (v) adding new or additional functional food ingredients to promote healthier mussels that are more disease resistant. Ongoing research and development for oysters includes: (i) selective breeding and (ii) OsHV-1 resistance, including better understanding of the disease, management, and selective breeding for disease resistance.

![Figure 18: Wild fishery shellfish declines. Left: standardized estimates for green lipped mussel landings for the Nelson/Marlborough region. Right: trends in oyster population size recruits, pre-recruits, and landings.](image)

### 10.5 Industry questions for science

(Summary of presentation by Ted Culley)

Recognizing the changes in ocean acidity, the problems that the shellfish industry is addressing, and the need for suitable applicable methodologies and solutions, questions from aquaculture industry for the scientific community were raised:

- When will we see effects of ocean acidification on the shellfish industry, or are they already here?
- What kind of effects will we see?
- Given our heavy reliance on wild spat, how resilient is our supply? Are the problems of the U.S. Pacific Northwest coming our way?
- Will the impacts of ocean acidification be severe and can those impacts be mitigated?
- How sensitive are mussels to pH and different levels of calcium carbonate? How much will the work on oysters from the Pacific Northwest be transferable to New Zealand?
- Are the impacts of ocean acidification localized or general? Will they be evident across New Zealand or will some areas be more sensitive? We need to look more closely at our changing water profiles and quantifying those changes.
- How much of our shellfish production is subject to upwelling of acidic water?
- Will there be direct physiological effects? Selective breeding may play an increasingly important role in the future.
• How do we protect the industry? A hatchery can only do so much if the goal is to obtain higher levels of production. If hatcheries take on greater importance, greater spat volumes and the manipulation of water chemistry may be important.
• Can we manipulate our local water chemistry in our spat farms and sea farms, e.g., buffering habitats with crushed shell? Perhaps legislation will need to be modified to facilitate the use of mitigation strategies and the use of different locations for cultivation.
• Guidance will be required so that water intakes are not compromised, on knowing what areas may be at highest risk, and to future-proof our current locations.

10.6 Learning and adapting

(Summary of presentation by Ted Culley)
The industry is potentially already feeling the effects of ocean acidification and processes could be modified to increase resilience. However, dedicated funding doesn’t exist within the industry to make the modifications. An ecosystem-wide problem will require a large investment to find science-based solutions. New Zealand has a new initiative, the National Science Challenges, funded with NZD $60M to 2016, and $30.5M annually thereafter. One of the challenges includes “Sustainable Seas” which may be relevant to the shellfish aquaculture industry and the impacts of ocean acidification (PMCSA 2014).

10.7 Finfish aquaculture, Chinook salmon and wild fisheries

(Summary of presentation by Ted Culley)
What is the outlook for how ocean acidification will impact finfish aquaculture in New Zealand? While Chinook salmon can tolerate a relatively wide pH range, are there subtle effects of pH on other compounds in the water? Even if ocean acidification has no obvious physiological impact on the fish will it make fish that are currently are disease-free more susceptible to disease?

Also important is to better understand the impacts of ocean acidification on low trophic levels that could impact finfish aquaculture and to understand the impacts of ocean acidification on wild fisheries, for example, the rock lobster fishery (2752 mt), the dredge oyster fishery (1256 mt), the cockle fishery (1058 mt), the paua fishery (944 mt), and the scampi fishery (705 mt).

11 GREENSHELL MUSSEL (PERNA CANALICULUS) VULNERABILITY TO OCEAN ACIDIFICATION

(Summary of presentation by Norman Ragg)
The Cawthron Institute considers that risk mitigation is key to long term success in aquaculture. Ragg considers that the free swimming larvae of P. canaliculus may be New Zealand’s ‘canary in the coal mine’ for seawater conditions and greenshell mussel survival. Until recently, the industry was entirely reliant upon unreliable wild-gathered spat supply. Cawthron in partnership with Kono and SPATnz has sought to secure spat supply using land-based hatchery and nursery systems. The stages of fertilization to spat occur in the hatchery while the juvenile to adult stages occur in the open ocean. Spat are attached to a fibrous substrate for deployment out to sea.

In the 1990s, Cawthron closed the mussel life-cycle knowledge gap and developed hatchery technology. In 2002, they began a selective breeding programme, including the use of a flow through, high density larval rearing system, which is conducive to high densities (e.g., 800 individuals/mL). By November of 2014, SPATnz will be producing commercial quantities of P. Canaliculus spat.
11.1 Potential vulnerabilities \( P. \text{canaliculus} \) veliger larvae to ocean acidification

- The adult shell is pure aragonite
- Sperm motility and fertilization are pH sensitive
- Calcification of the first shell
- The byssus attachment is sensitive to pH

The free swimming \( P. \text{canaliculus} \) veliger larvae is one focal point of the Cawthron Institute’s research program because the first two weeks of life is the period during which most problems become manifest. Ragg also believes that parental history is also important to veliger larvae survival. Characteristics of the veliger larvae include:

- They have a delicate pelagic phase lasting 3–6 weeks
- They must sequentially grow two aragonite shells: Prodissoconch I and II
- They are constant swimming, dynamic feeders
- They are vulnerable to malformation
- They are a key ecological and production bottleneck
- They lack specialized ion-regulatory epithelia required for managing acid-base status

11.2 The impacts of variable pH on early \( P. \text{canaliculus} \) veliger larvae

Beginning with two day old free swimming larvae, the impact of pH on shell growth up to 12 days was examined. At pH values of 7.3, 7.7, 8.0, and 8.3, there was little change in the percentage survival. Using shell length as a proxy for growth, significant effects were observed comparing results obtained at pH 7.3 and 7.7 with those obtained at pH 8.0 and 8.3. Looking at the percentage of 12 day old larvae that reach settlement size (over 200 \( \mu \)m) there was a marked pH dependence (Figure 19). Calcification was measured by assessing shell thickness which showed an increase over the range of pH 7.3–8.3 of 2.7 – 5.1 \( \mu \)m) (data not shown).

![Figure 19: Effect of pH on the percentage larvae reaching settlement size (over 200 \( \mu \)m).](image)

11.3 Preliminary conclusions

- Larvae survived and produced calcified shell even at values of \( \Omega_{Ar} \) less than 1.
- Larvae show resilience to extended incubation in near-future pH scenarios.
- Synergistic effects upon growth and survival may have dramatic implications for metamorphosis and recruitment.
- There appears to be room to improve calcification and general performance beyond present day CO\(_2\) conditions by creating more favourable growing conditions (lower CO\(_2\)). This point is particularly relevant to New Zealand where cataclysmic problems do not yet exist and suggest the opportunity to take steps that can enhance performance.
11.4 Looking forward: Priorities for understanding the implications of ocean acidification on *P. canaliculus* production

Mitigation and resilience- what needs to be done?

**Phase 1: Land based systems:**

- Monitoring of incoming seawater carbonate parameters in New Zealand; e.g. Cawthron Aquaculture Park, which contains New Zealand’s only mussel and oyster hatcheries and land-based nursery, as well as shellfish research facilities. This is essential for the country as there is little information on carbonate levels (apart from one time series) across time and geography (Section 9.1).
- Chemical enhancement of calcification.
- The use of ultra-dense larval cultures presents opportunities to understand calcification chemistry due to the high densities of larvae amplifying the subtle changes in water chemistry due to biological influence.
- Microcosm studies of acidification effects on larvae and dietary microalgae in the same space provides research opportunities to assess the influence of ocean acidification on grazer and algae interactions.
- Energy budget: we need to better understand the energetic costs of shell formation to the animal.
- Determine the influence of pH on spat retention (the proportion of juvenile shellfish that survive and remain attached to culture lines), arguably the key biological source of concern in the production cycle for the industry.

**Phase 2: Ocean based grow-out:**

That much of the production cycle occurs in the highly variable open ocean is tremendously challenging when looking to enhance resilience. Selective breeding for enhanced resilience to increased volatility in coastal growing conditions is a priority. Parker et al. (2011) showed that the experience of the pre-spawning adults has some downstream beneficial effects on larval resilience. Exposing adults to acidified water could provide enhanced resilience to next generations.

A range of susceptibilities to environmental stress tolerance have been demonstrated within strains of *Perna* developed by Cawthron. The institute currently has more than 150 families of *Perna*, a highly successful breeding programme focusing on bulk production, and a great deal of genetic diversity at its disposal. A natural extension of the stress tolerance work is to explore high pCO₂ resilience among different mussel strains.
12 OCEAN ACIDIFICATION IMPACTS ON NEW ZEALAND ABALONE, COCKLE, AND FLAT OYSTER

(Summary of presentation by Vonda Cummings)

The biological effects of ocean acidification vary depending on species, life history stage within a species, and location: e.g., variable responses in the same species originating from different regions.

12.1 Shell carbonate mineralogy varies between organisms

- New Zealand cockle, also known as the little neck clam (*Austrovenus stutchburyi*) has shells which are aragonite, which is 30% more soluble than calcite.
- New Zealand abalone, also known as paua (*Haliotis iris*) has shells which are bimineralic, calcite and aragonite.
- New Zealand flat oyster also known as the dredge or Bluff oyster (*Ostrea chilensis*) has shells which are low magnesium calcite.

12.2 Experiments conducted on juvenile phases of the cockle, abalone, and flat oyster to assess the impacts of variable pH and/or temperature

The experimental scenarios tested were based on temperature predictions for oceanic New Zealand in 2050 and 2100 (range 11 – 21°C) and a pH decline of 0.3—0.4 pH units by 2100.

The effects of changing pH alone (at a constant temperature of 15°C) or temperature alone, as well as interactive effects of pH and temperature, were investigated.

![Figure 20: Cockle, Abalone (paua), and Flat oyster](image)

Response variables measured abalone, cockle, and flat oyster (5—14 months old):
- Survival
- Growth
- Physical condition
- Physiological condition
- Effect of pH (at 15°C) or temperature gradient alone
- Interactive effects of pH and temperature
- Relationship with carbonate saturation states

12.3 Conclusions

- Both warming and acidification will affect these populations in the future.
- For each species, the scenarios tested affected almost all of the response variables we assessed.
• Interactive effects of temperature and pH were noted for abalone and cockles, but flat oysters were most strongly affected by changes in temperature.
• Negative influences on responses were observed even when carbonate saturation states were above 1, indicating cause for concern even before environmental conditions reach undersaturation.

12.4 Future work
• Multiple stressor, in situ/in vivo experiments and observations; incorporating natural variation in environmental parameters, community composition, etc.
• Investigating the relative susceptibilities of key mollusc species. A detailed response of shell mineralogy, composition and structure is required
• Assessing the natural variation in pH. New Zealand coastal data is lacking and robust monitoring is urgently required.

13 ECOSYSTEM IMPACTS OF OCEAN ACIDIFICATION: NEW ZEALAND PERSPECTIVES

(Summary of presentation by Cliff Law)

Phytoplankton are responsible for much of the CO2 uptake in the oceans. In coastal zones, macroalgae are also important to the carbon cycle. Also affected by acidification is the availability of trace metals and nutrients which affect the growth of phytoplankton, macroalgae, and bacteria. Organisms that rely on CaCO3 will also be impacted, including cold water corals and calcifying planktonic organisms such as coccolithophores. Fish behaviour and physiology can also be affected, changing carbonate chemistry.

13.1 Impact of ocean acidification on bacterial degradation of organic matter

Twenty-seven percent of anthropogenic CO2 has been taken up by the ocean, a proportion of which is fixed by phytoplankton. There are bacteria that modulate this process by converting CO2 that has been fixed by phytoplankton back into CO2. Bacteria cannot break down large organic substances such as proteins and carbohydrates and thus release enzymes into the water whose activity is then affected by the pH of the ocean, a process that could be affected by ocean acidification. In regions around New Zealand and the Ross Sea where the impact of pH on these enzymes has been studied, protein and carbohydrate degradation increases under high CO2 conditions (Maas et al. 2013). This is consistent with published studies in other regions and suggests that ocean acidification may increase respiratory CO2 production and cause a short circuiting of CO2 uptake, potentially reducing the ocean’s capacity to sequester atmospheric CO2.

13.2 Are nitrogen fixers potential “winners” under ocean acidification?

Nitrogen fixation is an important source of new nitrogen in warmer, nutrient-poor waters. About 50% of the surface ocean is short of nitrogen including tropical and subtropical waters north of New Zealand. Nitrogen fixation by the large phytoplankton, Trichodesmium sp., increases the rate of nitrogen fixation by 30–120% under elevated CO2, which could result in a large increase in nitrogen input into these systems. However, New Zealand waters do not contain Trichodesmium sp. and nitrogen fixation is instead accomplished by a unicellular cyanobacteria which shows no response to changing CO2. These results show that nitrogen fixation in New Zealand waters will remain unaffected by changes in CO2 and there will be no increase in the nitrogen supply. Productivity in
New Zealand waters is a larger and more complicated issue affected by a variety of factors (i.e. runoff). Ocean acidification’s likely impact on primary productivity remains uncertain.

13.3 Coastal macroalgae communities under declining pH

The coastal zone in Otago was studied for winners and losers under rising CO₂ levels. Crustose coralline algae use carbonate and so the projected future reduction in carbonate of 50% by 2100 (from 206 to 121 μmol/L globally; RCP8.5 in IPCC (2013), Bopp et al. (2013)), may result in reduction in growth. Kelp use bicarbonate and CO₂ and may benefit from higher growth rates under future conditions as both of these carbon sources may increase. Conversely crustose coralline algae may decline as they use carbonate ions, which will decrease as the ocean acidifies. Red algae that live under low light may be winners, as they may benefit from the doubling of CO₂ projected for year 2100. Overall the change in availability of the different carbon species may result in changes in dominant macroalgae and alter coastal ecosystems. (Hepburn et al. 2011).

13.4 Relationship between cold water coral distribution and aragonite saturation horizon (ASH)

The ASH describes the boundary above which aragonite is stable and below which it dissolves. Scleractinian cold-water corals use aragonite and provide important habitat and refuge for larvae, invertebrates, and fish. They are currently at or above the current ASH which varies between 1000 and 1200 m. In the future, it is estimated for New Zealand waters that the ASH will shoal to approximately 600 meters. This means that in 2100 less than 25% of current coral locations will be above the ASH, putting their survival at risk. (Bostock et al. 2013, Tracey et al. 2011, 2013).

13.5 Impact of ocean acidification on echinoderm larvae

Echinoderms, urchins and sea stars are important keystone species in coastal ecosystems. Larval development in species from tropical through to temperate regions has been studied to assess how they would respond under high CO₂ environments (Byrne et al. 2013, O'Donnell et al. 2010). The overall trends show:

- Smaller larvae with increased malformation.
- Genes for energy metabolism and biomineralization down-regulated (less active).
- Decreased feeding efficiency and increased time in planktonic phase and hence increased susceptibility to predation.
- Decreased probability of survival.

14 LINKING OCEAN ACIDIFICATION, EUTROPHICATION, AND LAND USE

(Summary of presentation by John Zeldis)

How ocean acidification is linked to eutrophication and land use is particularly important in New Zealand. Acidification and eutrophication stressors are linked by interacting nutrient, carbon and oxygen cycles in the coastal sea (Figure 21). One expression of these interactions is Net Ecosystem Metabolism (NEM), described by the equation:

\[
\text{CO}_2 + \text{inorganic nutrients} + \text{water} \leftrightarrow \text{organic matter} + \text{oxygen}
\]

NEM describes how organic matter is formed (from left to right) and how it decomposes (from right to left). The balance of this equation defines the net ecosystem metabolism.
14.1 How is NEM linked with acidification and eutrophication?

One way that they can be linked is by measuring the propensity of the coastal environment to emit or consume CO$_2$, often measured as dissolved inorganic carbon (DIC), which is important in global CO$_2$ budgets and climate studies. As the CO$_2$ concentration increases, pH decreases, reducing the concentration of carbonate ions available for calcification and leading to corrosive water (Figure 1). NEM is also a measure of eutrophication in which excess oxygen consumption occurs, fuelled by inorganic nutrient loading and the decomposition of phytoplankton blooms, which consumes oxygen and generates CO$_2$.

14.2 Assessment of NEM in the Hauraki Gulf and Firth of Thames

NEM was assessed in the Hauraki Gulf and Firth of Thames. The central North Island is the most intensively farmed region in the country and set to expand with dairy farm intensification (Figure 21) (Zeldis 2006).

![Figure 21: Locations where seasonal surveys were conducted to assess temperature, salinity and nutrient composition in the Hauraki Gulf, Firth of Thames, Golden Bay, and Tasman Bay. Modelling was used to evaluate the transport of water and salt in and out of the system (blue and green arrows) which was compared to the transport of nutrients across the same boundaries.](image)

The results showed that catchment nitrogen loads (organic and inorganic) are much higher in the Firth of Thames than in the Hauraki Gulf or Nelson Bays. The Hauraki Gulf and Nelson Bays are weakly autotrophic (DIC consumed) whereas the Firth of Thames is strongly heterotrophic (high generation of DIC into the water and CO$_2$ into the atmosphere through respiration).
The high anthropogenic loads of nitrogen in the Firth of Thames is due to the nitrogen content of Waihou and Piako rivers that empty into the catchment. Both rivers have high nutrient loads when compared to the rivers that flow into Golden and Tasman (Nelson) Bays (Unwin et al. 2010).

The Firth of Thames is an iconic area of New Zealand, sustaining the largest individual mussel and oyster farms in the country. Expansion plans for these farms and large fish farms are underway. The Firth of Thames is also the site of New Zealand’s largest snapper larval nursery, nursery for the country’s most important recreational and commercial coastal fish stock.

14.3 Long term monitoring program in the Firth of Thames

A long term monitoring program would shed light on how terrestrial components are affecting ocean acidification in the Firth of Thames. The carbon system was assessed through direct measurements in autumn 2010 and showed pCO₂ to be highly oversaturated, especially off river mouths, with pH values as low as 7.9 – the level forecast for the open ocean in 2060, i.e., pH values that are ‘ahead of the curve’.

14.4 Conclusions

- Eutrophication and acidification are linked through multiple biogeochemical cycles involving N, O₂, and CO₂.
- These stressors need to be understood as a package of effects.
- Nitrogen, carbon and oxygen cycles, and hypoxia need to be included when assessing the impacts of acidification.
- These systems are highly variable in space and time and a better understanding is necessary.

14.5 Next steps

- Complete the seasonal series – to measure the spatial relationships of hypoxia, pCO₂/pH, and bio-optics.
- Investigate high-frequency variation in oxygen using Firth of Thames mooring and assess underlying drivers.
- Install pH sensor, bag sampler, and new bio-optical instrumentation on the Firth of Thames mooring.
- Use nutrient budgets to determine relationships with catchment loading/ocean inputs.
15 PROJECTED CHANGES AND MONITORING OF THE MARINE ENVIRONMENT: NEW ZEALAND POLICY FRAMEWORK AND KNOWLEDGE TRANSFER

(Summary of presentation by Mary Livingston).

Science policy, funding mechanisms and the recognition of the role of monitoring for environmental reporting have been going through a dramatic period of change over the past 20 years in New Zealand. But, it is only really in the most recent years that the marine environment has come into focus. Calls for improved marine research, and also monitoring of the marine environment, have become increasingly prominent in documents such as Briefings to Incoming Ministers, as concerns about phenomena such as ocean acidification, warming seas, and changes in fish distribution have filtered through the media to the general public, to fishing and aquaculture industries and to managers responsible for living marine resources.

The New Zealand government has also placed growing the marine economy firmly on the Business Growth Agenda, particularly with regard to petroleum and mineral resources. New legislation has been introduced around extraction (Exclusive Economic Zone and Continental Shelf [Environmental Effects] Act 2012 [www.mfe.govt.nz]), and more is in the pipeline (e.g. draft Environmental Reporting Bill www.mfe.govt.nz/environmental-reporting; Marine Reserves Bill [www.parliament.nz]). Statistics New Zealand completed its Environmental Domain Plan and reviewed the environmental Tier 1 Statistics for New Zealand, identifying two new marine statistics for development. The government is also developing a suite of National Science Challenges, including one entitled “Sustainable Seas” that will inject new funding into marine research. Alongside this, an overarching twenty year national marine research strategy is being developed (www.mbie.govt.nz › What we do).

While there may be some new opportunities afforded by ocean acidification and climate change effects on the sea, the changes in the ocean are recognized as likely to pose considerable risks to New Zealand’s marine environment and its living resources. Some of these effects will be lethal and others will be sub-lethal, and the effects will vary within a given organism’s life history.

Aquaculture and shellfish industries, as well as fisheries are likely to be affected. Biodiversity and ecosystem services will also most likely be affected. It is important therefore that among the suite of considerations underway to identify marine issues and marine research priorities for New Zealand in the coming years, that the threats to living resources be clearly identified, and that monitoring and practical mitigation steps be taken so as to minimize these effects. It is crucial that scientists and industry articulate their concerns clearly to government, particularly given the surge in political interest in the marine economy.

16 CONCLUSIONS AND RECOMMENDATIONS

The ocean acidification workshop was an extremely successful event that brought the New Zealand aquaculture industry, scientists and managers together for the first time to discuss how we can best prepare for inevitable changes in ocean chemistry and learn from recent experiences in the U.S. It was the first step of many and valuable connections were forged between industry, science and government within New Zealand. The workshop also strengthened New Zealand’s scientific partnership with the U.S. under the umbrella of the N.Z.–U.S. Joint Commission on Science and Technology Cooperation (JCM) that fosters scientific exchange and collaboration between our two countries. It is recommended that New Zealand build on the momentum created by the workshop with the following actions:

1. Continue work to secure the involvement of the New Zealand aquaculture industry and regional councils in a new ocean acidification monitoring network planned for New
Zealand, and link to other marine environmental monitoring work underway, for example, by the Ministry for the Environment and Regional Councils.

2. Support and promote the establishment of a nationwide coastal monitoring network to provide information on spatial and temporal variation in carbonate parameters at key locations in New Zealand, including those of interest to the shellfish aquaculture industry. These sites should ideally conform to GOA-ON standards so this information can contribute to global efforts.

3. Strengthen collaboration among all interested groups with the New Zealand Ocean Acidification Research Group and others working on ocean acidification in New Zealand. Explore the utility of establishing an Ad Hoc Ocean Acidification Steering Committee to guide future planning efforts.

4. Continue to promote collaboration and information sharing between the U.S. and New Zealand on ocean acidification, particularly on issues relating to shellfish aquaculture in New Zealand.

5. Build on the working relationship developed during the workshop with U.S.-based scientists and marine farmers to leverage opportunities for future technology transfer and general exchange of knowledge pertinent to ocean acidification and its impacts in New Zealand.

6. Identify opportunities to expand the value and outcomes of the scientific developments with respect to ocean acidification in New Zealand that may benefit other Pacific nations in the region.

17 KEY POINTS FOR INDUSTRY

1. The carbonate chemistry of the oceans is changing globally, including in New Zealand waters. This process has been termed ocean acidification. Worrisome oyster larvae declines (mortalities up to 80%) have occurred in the U.S. Pacific Northwest that were directly attributable to ocean acidification. New Zealand will not be immune from these changes in ocean chemistry and the message from the U.S. shellfish industry/science speakers was clear. It is better to be prepared, than not.

2. The U.S. Pacific Northwest experiences strong upwelling events that bring waters rich in CO2 to the surface, causing problems for shellfish along the U.S. West Coast. New Zealand does not experience upwelling of this magnitude, but similar high CO2 conditions are predicted for New Zealand waters in the coming decades as carbon dioxide emissions increase. Ocean acidification will persist for centuries due to time lags in the carbon system and the amount of CO2 currently in the atmosphere.

3. Ocean acidification effects vary among marine species with some being more sensitive than others. Many species of shellfish (i.e. Pacific oyster) are particularly vulnerable, whereas other species (i.e. seagrasses) will probably benefit from higher CO2 levels. The overall marine ecosystem responses of the species that benefit and are negatively impacted by ocean acidification are not well understood.

4. Early larval stages of Pacific oysters are most sensitive to ocean acidification. Alan Barton, Whiskey Creek Shellfish Hatchery, stated that their hatchery’s ‘break even’ point for larval survival (70% survival rate) is $\Omega_{Ar} = 1.7$.

5. Taylor Shellfish Farms have increased capacity at existing shellfish hatcheries in Washington state and opened additional hatcheries in Kona, Hawaii to diversify and offset loses of increasingly acidified waters in the U.S. Pacific Northwest.

6. Both Whiskey Creek and Taylor Shellfish have recovered most of their production by monitoring the $\Omega_A$ of intake water, not filling water tanks for rearing shellfish when $\Omega_{Ar}$ is unfavourable, and chemically treating hatchery water to increase $\Omega_{Ar}$.

7. Adding crushed shell to surrounding waters to help buffer increasingly acidified water may help increase survivorship for some species (i.e. soft-shell clams).
8. Monitoring carbonate chemistry in the coastal zone and hatchery intakes is critical for future-proofing industries to the best extent possible. Different technologies and methodologies are required.

9. pH is rarely the driver of biological responses, $\Omega_{Ar}$ is the variable that should be calculated (see Section 8.2 for details) and monitored. Determining $\Omega_{Ar}$ is expensive (see Sections 8.4 and 8.6 for details on effort and costs) and can require discrete bottle sampling and technical support. Coastal stations, including hatcheries, with access to pumped seawater streams offer many benefits over remote moorings.

10. The water chemistry of the coastal zone is very complex due to terrestrial influences including land-use, freshwater runoff, and nutrient loading. Land-use practices can be modified to potentially reduce negative impacts of unfavourable water chemistry. Hypoxia and ocean acidification may be linked, but the relationship between the two is not yet clear.

11. Fostering and supporting research into the physiological impacts of ocean acidification on aquaculture species will enable industry to explore practical ways to mitigate the negative effects (e.g. through selective breeding programmes, exploring the advantages of closed hatchery systems).

12. The New Zealand industry obtains 80% of Greenshell mussel spat from Ninety Mile Beach in Northland (Kaitaia). The source(s) of this wild spat is unknown. Investigation into determining the source(s) of this wild spat is warranted given industry’s heavy reliance upon it (and therefore potential vulnerability).

13. The Cawthron Institute and partners (Kono and SPATnz) are actively trying to secure Greenshell mussel spat supply from land-based hatchery and nursery systems to reduce dependence on wild spat and risk.

14. Mussel retention may be enhanced by adding horizontal structure to culture ropes, keeping stocking densities low, by avoiding silted waters or hanging the rope too low, or by selective breeding for mussels that have stronger attachment.

15. Both warming and ocean acidification will impact populations of New Zealand cockle, paua (abalone), and flat oyster (dredge or Bluff oyster). Negative influences on responses were observed when $\Omega_{Ar}$ was greater than 1.

16. Fish behaviour and physiology can be affected by ocean acidification. The implications of this for the finfish aquaculture industry and wild fisheries remain unclear as responses vary by species and research is in its infancy.

17. Impacts of ocean acidification on wild populations of shellfish and by extension wild shellfish fisheries remain uncertain.

18. It is critical that scientists and industry representatives articulate their ocean acidification concerns clearly to government, particularly given the surge in political interest in the marine economy.

18 ACKNOWLEDGEMENTS

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19 REFERENCES


APPENDIX 1. WORKSHOP PROGRAMME

Organising Committee: Anna Crosbie and Mary Livingston (MPI); Vonda Cummings and Di Tracey (NIWA), Norman Ragg (Cawthron Institute), Todd Capson (SFP), and John Guinotte (MCI).

Tuesday, December 3rd. Ocean acidification: overview and issues
9:00 am. Official Opening
Mihi Whakatau (a traditional welcome ceremony) from Archdeacon Harvey Ruru

Welcome from Kathy Mansell, Director Aquaculture, Growth and Innovation (MPI)

Welcome from Marie Damour, Deputy Chief of Mission, U.S. Embassy, Wellington

9:25 am. Introduction from facilitators, John Guinotte and Todd Capson
Aim of the workshop and anticipated outputs, objectives of day 1, introduction to ocean acidification

9:40 am. Bill Dewey, Taylor Shellfish Farms
Ocean acidification has arrived at our shores: An industry perspective on the U.S. Pacific Northwest oyster crisis

10:10 am. Kim Currie, NIWA/University of Otago Research Centre for Oceanography, and Cliff Law, NIWA
The chemistry of ocean acidification, broader ecosystem impacts: NZ perspectives

10:40 am. Richard Ford, MPI
A tale of two species: NZ shellfish aquaculture-species, geography, methods, oceanography and economic importance

11:40 am. Ted Culley, Aquaculture Manager, Sanford Ltd.
Ocean Acidification – A perspective from the New Zealand shellfish industry

12.00 pm. Burke Hales, Oregon State University
Ocean acidification in upwelling systems: Why natural variability makes a bad thing worse

1:30 pm. George Waldbusser, Oregon State University
Coastal zone ocean acidification: What matters to oyster larvae and why

2:00 pm. Emily Carrington, University of Washington
Environmental linkages to mussel sloughing in natural and farmed populations

2:30 pm. Norman Ragg, Cawthron Institute
NZ Greenshell mussels: Breeding strategies to accommodate climate change

3:30 pm. Vonda Cummings, NIWA
NZ shellfish, ocean acidification and warming: Juveniles are affected too

4:00 pm. Q & A and facilitated panel discussion: all speakers available to answer questions
5:00 pm. End of day 1 presentations and discussion

Wednesday, December 4th: Monitoring, management, mitigation & adaptation
8:30 am. John Guinotte and Todd Capson
Introduction from facilitators – aim of day 2 and anticipated outputs
8:45 am. Bill Dewey, Taylor Shellfish Farms
One business’ response to ocean acidification

9:15 am. Alan Barton, Whiskey Creek Shellfish Hatchery
Greetings from the coal mine: The nuts and bolts of running a shellfish hatchery with acidified water

9:45 am. Burke Hales, Oregon State University
Getting past the pH problem: Measurement and observation approaches that will let you get it right

10:45 am. Kim Currie, NIWA
Global ocean acidification monitoring network and NZ-specific plans

11:15 am. Bill Mook, owner, Mook Sea Farm
Preparing for climate change and ocean acidification in a Maine oyster hatchery (via Skype)

11:45 pm. Q & A

1:00 pm. George Waldbusser, Oregon State University
Feedbacks among shell production, dissolution, larval settlement, and ocean acidification

1:30 pm. Emily Carrington, University of Washington
Improving retention in mussel rope cultures: what are the data bottlenecks?

2:00 pm. John Zeldis, NIWA / University of Auckland Institute of Marine Science
Multiple stressors on marine ecosystems that act in concert with OA

2:30 pm. Mary Livingston, MPI
Projected changes and monitoring of the marine environment: New Zealand policy framework and knowledge transfer

3:30 pm. Q & A and facilitated discussion
Identification of monitoring, mitigation and adaptation priorities for NZ

4:30 pm. John Guinotte and Todd Capson
Wrap up by facilitators
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