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Sea changes

PROFESSOR DAVID M. PATERSON

Most of us who live in Scotland find ourselves attracted to the sea, and most of us can reach the coast quite easily. So it is no surprise that the history and culture of Scotland is closely interwoven with maritime development and exploitation of marine resources.

Today, we think in terms of our current requirements for energy (oil and gas, wind, wave and tidal) and food (fisheries and aquaculture), but we are also beginning to recognise that many marine resources are finite and many practices will have to change – including how we harness energy and the source and type of food we eat.

Not all of these changes are caused by local exploitation in Scotland. As discussed on pages 32–37 of this issue of *Science Scotland*, global climate change may have a major impact on Scottish waters and we will have to understand and manage these effects. Some common local species may disappear and new species arrive as waters increase in temperature, whilst acidification of the coastal waters may lead to changes in the form and function of some ecosystems with – as yet – unknown consequences.

There are challenges on the horizon, but Scotland is well placed to address these issues. In keeping with our marine heritage, we have a distinguished history of marine research dating back even before the legendary *Challenger* expedition organised by the University of Edinburgh in 1872, which catalogued 4,000 new marine species and allowed Sir John Murray to describe the results of the voyage as "the greatest advance in the knowledge of our planet since the celebrated discoveries of the fifteenth and sixteenth centuries."

Today, we use much more advanced technologies – including satellites and sensors and molecular biology – but many of the questions are the same: How does the marine system work? What is the extent of its biodiversity, and how can we safely and sustainably exploit it? How fast is the system now changing and why?

Scotland has great talent and resources in its universities and institutes, and in the government organisations and commercial businesses that concern themselves with the marine environment, and this issue provides an insight into some of the people and technologies that are being deployed to find the answers we urgently need.

Professor David M. Paterson, Scottish Oceans Institute, School of Biology at the University of St Andrews, and Executive Director of MASTS (the Marine Alliance for Science and Technology for Scotland)

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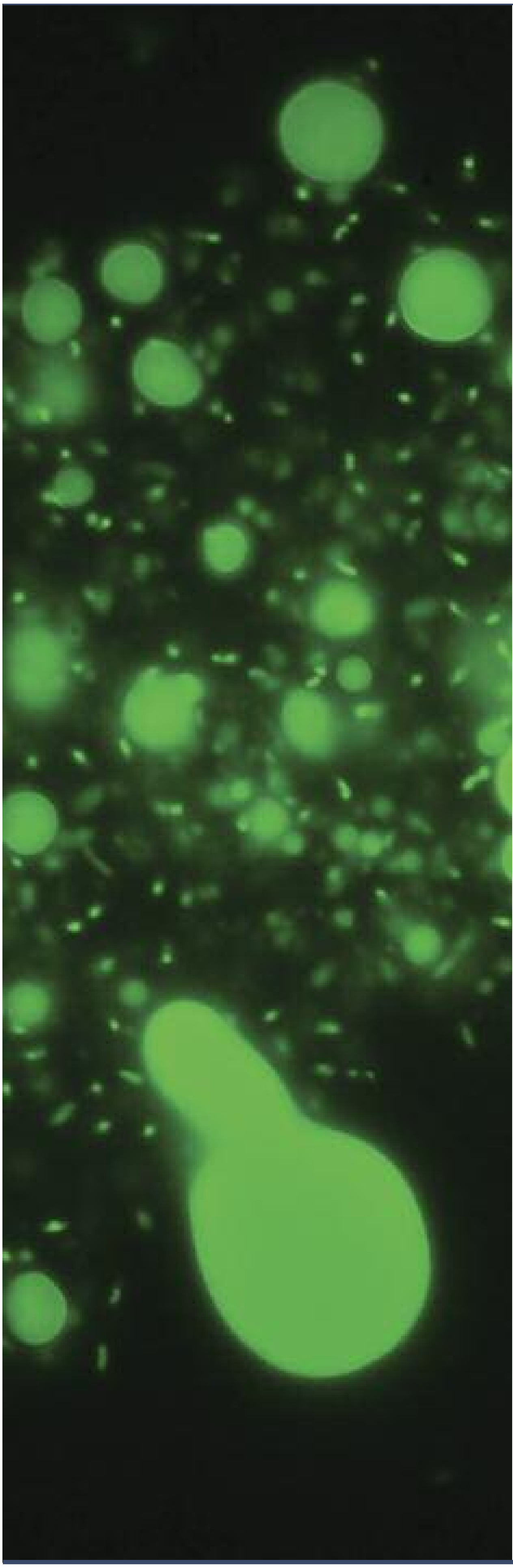

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International Perspective

From jellyfish, dolphins and seals in the waters off Scotland to amphipods 10,000 metres down in the Kermadec trench near New Zealand, the research going on in Scotland is diverse and international – and the PhD students themselves come from countries all over world (including Scotland).

Chad Widmer

University of St Andrews

The effects of climate variability on life history stages of British jellyfish

Chad first came to St Andrews on vacation and liked it so much he is now a post-graduate there, writing his Thesis on jellyfish. In fact, it was his sighting of a blue fire jellyfish on the beach at St Andrews that first sparked his interest. Having spent 13 years working at an aquarium in California, Chad had also developed a strong interest in conservation. His research into jellyfish investigates "why we see them, where we see them" in relation to climate – e.g. they are more common after cold winters and grow more quickly during warm summers. What mechanisms drive this and what can we learn about climate (including temperature and salinity) by studying jellyfish?

Chad has also advised Scottish fish farms on how to control their jellyfish populations, which can harm their salmon. For example, the platforms used for cages can be ideal breeding grounds for jellyfish – home to ten polyps per square centimetre, each producing 20 jellyfish per year. Jellyfish are also a barometer of climate change, according to Chad, indicating when the ecosystem may be out of balance and reflecting short-term changes in climate.

Chad describes his project as follows: "Jellyfish play important roles in pelagic ecosystems, acting as zooplankton predators and food for a small host of organisms. Seasonally, they form blooms which facilitate their reproductive success, but these can sometimes be problematic for human enterprise. In the last few decades, the idea has arisen that the frequency and size of jellyfish blooms have been changing, increasing in some areas while decreasing in others. However, the direct causes for these changes are unclear. Jellyfish medusae abundance depends on success at all stages of the life cycle. Therefore, to better understand how climate variability may affect the timing of jellyfish blooms and their potential locations and magnitudes, it is important to study how factors associated with climate affect all jellyfish life history stages. I use the results from my laboratory experiments to generate basic statistical models which enable the prediction of the magnitudes of future jellyfish blooms. The general trend is that more jellyfish will be observed in British waters during summers following very cold winters, and fewer jellyfish will be observed following warm and mild winters."

Silje-Kristin Jensen

University of St Andrews

Is toxin from harmful algae the reason for the Scottish harbour seal decline?

Harbour seal populations in some parts of Scotland have declined dramatically in recent years, and Silje is investigating if this is caused by particular toxins produced by algae and then passed along the food chain. How do these toxins accumulate in fish, the staple diet of seals?

We know the toxins are found in the gut of the fish, which humans do not tend to eat, but predatory seals consume the whole fish, including the gut, and thus can be used as "sentinels of ocean health."

Along with Chad and eight of her colleagues at St Andrews, Silje regularly meets up with 40 other MASTS post-graduates from other institutions in Scotland. Back home in Norway, says Silje, a project such as MASTS could have a similar impact, and one day she would like to continue her work there.

Silje describes her PhD research as follows: "Phytoplankton are the most important organisms in the ocean and, under certain conditions, they can grow and reproduce quickly, forming what are known as algal blooms. Most of these blooms are beneficial to the ocean's ecosystem and form the basis of the marine food chain, but 'harmful algal blooms' (HABs) produce toxins at certain times in their life cycle, including those responsible for shellfish poisoning in humans, while a neurotoxin called domoic acid (DA) has been associated with the deaths of hundreds of California sea lions on the US west coast every year since 1998.

"From 2000 to 2010, there was an 85% decline in harbour seal populations on Scotland's east and north coasts, while populations on the west coast have largely been stable. The reason for these regional differences remains unclear, but one possible cause is ingestion of toxins from HABs. Preliminary results show that Scottish harbour seals are exposed to DA and other toxins, such as Saxitoxin and Okadaic acid, which have also been found in several species of their fish prey. By linking these findings with information on seal diet and foraging areas, we can begin to assess the health risk of HABs to harbour seal populations in Scotland."

Lauren McWhinnie
Heriot-Watt University

Aquaculture site selection: a GIS-based approach to marine spatial planning in Scotland

When Lauren McWhinnie attended a recent conference on coastal GIS (geographical information systems) in Vancouver, she was the only marine biologist present in a field usually dominated by computer scientists and planners. This was no surprise, because Lauren is also doing something "unusual" in her field, using GIS to identify the best sites for fish farms at the same time as protecting the environment – on a bigger scale than previous studies, and closely integrated with planning.

Having done her first degree in Marine and Freshwater Biology at Edinburgh Napier University, Lauren chose to do her PhD at Heriot-Watt University, using huge amounts of data to build up a picture of the seas around Scotland, to balance the competing needs for increased commercial production and minimal environmental impact, especially for sensitive environments.

"GIS was an underdeveloped tool in marine spatial planning," says Lauren, who has been working on her project for almost four years now, sponsored by Marine Science Scotland. "It had been used a lot on land, but not really tested in the marine environment." In the past, there had been many smaller-scale, localised studies, but Lauren has taken a broader approach and also, where possible, increased resolution to zoom in on very fine details. The latest zoning model developed by Lauren now incorporates climate change scenarios to aid long-term planning, and the methods developed could also be exported from Scotland to countries worldwide. "Other countries are also just starting to look at these issues," says Lauren, "and what works for Scotland could also work anywhere else, as long as you get the right data."

Lauren describes her study as follows: "I am currently developing and testing approaches to the implementation of Marine Spatial Planning in Scottish waters, and ultimately aim to propose a decision support tool for aquaculture development. This research will outline the development and application of a new prototype zoning scheme designed and tested specifically for Scottish waters, using a geographical information system. The primary aim is to devise a large-scale, ecosystem-based zoning approach for managing activities, designating areas according to their ecological features and existing management mechanisms, and devising a series of goals, objectives and strategies for each of those areas.
The ultimate aim is long-term protection of the marine environment, treating areas as whole ecosystems, whilst still enabling diverse activities to take place in a sustainable manner – to provide a tool to manage any potentially conflicting uses whilst still maintaining environmental integrity."

Enrico Pirotta
University of Aberdeen

Assessing the population consequences of disturbances caused by human development on marine mammal populations: a case-study on bottlenose dolphins in the Moray Firth Special Area of Conservation

Enrico's fascination with dolphins began when he was a young boy growing up in northern Italy, and today he is doing research which could help to explain their behaviour when human beings enter their environment. We may observe the dolphins moving away when a ship comes near, but what about the potential impact on their habitat of wind farms – and will they return? How long will they be displaced from their favoured feeding places?

After completing his first degree in biology in Italy and his Master's degree at the University of St Andrews, focusing on marine mammals, Enrico spent a few months working for a consultancy and doing wildlife conservation work in the Mediterranean Sea and in Africa, in Gabon and the Congo, where he was able to study the Atlantic humpback dolphin.

"I have always been fascinated by the complex social systems of dolphins." he says, "and the way they interact with their environment." Enrico acknowledges that dolphins are "charismatic" animals, but also points out that this makes them ideal for engaging the public when it comes to understanding the environment. "They are also very vulnerable to human development," he adds. "And the more I get into it, the more interested I am."

Enrico's work focuses on investigating the underwater acoustic behaviour of dolphins and modelling their distribution patterns to understand their habitat use and see how they're affected by human activities such as increased shipping or dredging in harbours. "We need to bridge the gap between short-term and long-term effects," he explains. "We see them change their behaviour, but they may resume it later – and we may not be there to observe it." To analyse this, Enrico has developed new modelling tools which help to map where the dolphins forage, overlapping this with shipping traffic and the behavioural effects of boat interactions, to quantify the overall impact and predict future effects. "The dolphins may stop foraging when ships arrive and lose energy moving away," says Enrico, "but they may also compensate for this."

The development is part of an international effort to study the impact of anthropogenic activity on marine mammals, and Enrico says that what makes this recent work different is the move away from merely studying changes in behaviour to the long-term effects.

Enrico describes his work as follows: "With the rapid rate at which human activities at sea are developing and diversifying, it is increasingly important to identify the potential consequences on marine life. However, for long-lived marine mammals, it is hard to detect effects at a population level. Therefore, although European legislation calls for the protection of the conservation status of populations of these animals, we are often limited to observing only short-term changes in behaviour, the significance of which is unknown. In the context of an international effort to address such problems, led by Professor John Harwood of the University of St Andrews, I am working with Dr David Lusseau at the University of Aberdeen to develop a modelling tool that can help to bridge this gap. My project focuses on a small population of bottlenose dolphins along the northeast coast of Scotland, which has been the object of intense study by Professor Paul Thompson and his team at the Lighthouse Field Station since the late 1980s. We have collected new acoustic data to investigate how dolphin foraging is impacted by boat traffic, and visual data to assess responses to coastal dredging. I am also using the existing long-term data to examine how individual dolphins use their habitat and which characteristics of the environment drive their foraging activity. By combining these elements with the distribution of boat traffic in the area, my aim is to develop a model that predicts the consequences of exposure to disturbance on individual dolphins. While considering the effects of boat traffic and coastal developments, these results could be adapted to other sources of disturbance of interest, such as offshore renewable energy developments. My work will hopefully help to guide management and conservation efforts, as well as streamline the consenting process for these important developments within Scotland and beyond."

Thomas Linley & Niki Lacey University of Aberdeen

Novel technology and fauna of the hadal zone

They swarm like bees, devouring the corpse of a fish, and then a giant comes along about 40 times bigger, followed by the strangest-looking fish you've ever seen, who rip the corpse to shreds and pick it clean, leaving behind just the bones. But humans have no need to fear. We could not survive here at depths of up to 10,000 metres, and soon after the fish and the amphipods are brought to the surface, they turn to jelly or explode.

This is not a horror tale, however, but part of two PhD projects involving Thomas Linley and Niki Lacey of the University of Aberdeen, who are using autonomous landers – like high-tech lobster pots with cameras and traps on board – to film and gather samples from one of the most remote and inhospitable places on earth, the Kermadec trench near New Zealand.

While Lacey looks for amphipods, underwater invertebrates related to "sand-hoppers" which range in size from 4mm in length to "giants" almost 40cm long, surviving by eating dead matter which falls from above, Linley hunts for strange fish (with strange names like "rat tail") that have never been seen before, except as bloated corpses caught in fishing nets.

"Neither humans nor these deep-sea creatures can survive where the other lives," says Linley. "We can never co-exist."

As well as studying the fish themselves, Linley also focuses on trying to improve or "update" the technology used for the dives – extremely strong structures with minimal weak points and minimal surface area, which are simply dropped into the water and sink to the bottom, then jettison their ballast to return to the surface. It's a "smart approach" to deep-sea research which is significantly cheaper, says Linley, than using remotely operated vehicles (ROVs) – very few of which can operate at such extreme depths. In addition, several landers can be launched at the same time.

"It's a technological challenge just to get down there," says Linley, "and not much is known about life down there." One advance in recent years has been the introduction of high-definition digital cameras with smaller, longer-lasting batteries, but at tens of thousands of pounds sterling per lander, including the payload, any further improvement is welcome.

The two researchers work very closely together, going together on missions about twice a year. Both are also interested in the same fundamental issues: what lives at the bottom of the trenches, where it lives and how it survives, as well as how the different creatures interact with each other. These deep-sea creatures have been known about since the 1950s, but largely neglected until recently in terms of research.

Linley and Lacey are also trying to establish connections between fauna in different places. Do groups stay in one place, and therefore evolve in a particular way, or manage to navigate over the undersea terrain which lies between trenches? Some amphipods seem able to survive at a wide range of depths – from 2,000 to 7,000 metres. How is this possible?

One obvious difference between their two projects is when the traps come back up to the surface and the crew get excited when they see the sometimes large and very strange-looking fish which appear, but hardly notice the amphipods because they are so similar looking and small.

When the bottom-dwelling creatures arrive on the boat, it's a race to preserve them – e.g. the fish begin to "fizz" and turn to mush within 20 minutes unless samples are quickly frozen using liquid nitrogen. That is why these creatures were so little understood until very recently – the only specimens were grossly distorted in appearance.

The "super-giant" amphipods recovered by Lacey are just one of the achievements of her research so far, "adding to the diversity of the species discovered" as well as finding species in places where they've never been recorded before. Part of her work also involves analysing the fatty acids in the amphipods in the bid to understand how they manage to survive at different depths, including understanding their feeding habits. "We know so little about them," she says, explaining that the same kind of organisms can also be found on land.

For Linley, one new area of future research would be to model the behaviour of the fish, which "pose for photos" in front of the lander, arriving to compete for the bait.

To discover an entirely new species would be a significant breakthrough – and who knows what is lurking at the bottom of the sea? "Every time a lander comes up," says Linley, "we don't know what we'll get – either as an image on the memory card or a specimen inside the trap."

Interview **Dr Bhavani Narayanaswamy & Dr Robert Turnewitsch**

Science at the deep end

The deep sea and its sea floor are now viewed as the largest and also the least explored ecosystem on Earth. This contrasts with the view – held as recently as only about 150 years ago – that there was no life at all more than 600 metres below the surface of the sea. Nowadays, as industry seeks to exploit marine resources (fish, hydrocarbons and minerals) at greater depths than ever before, scientists are accelerating their research to balance economic and environmental interests – as well as simply understand the mysteries of the Earth's "inner space."

The pressure on the deep is greater than ever, because of the rapid depletion of biological and mineral resources on land and in shallower waters. One of the challenges facing all deep-sea researchers, both in Scotland and elsewhere, is that "everyone and no-one is responsible" for what happens out in the depths of the ocean – certain aspects of human intervention affect large parts of the deep sea and in some cases the whole planet. "There are no boundaries in deep-sea research," says deep-sea biologist Dr. Bhavani Narayanaswamy of the Scottish Association for Marine Science (SAMS). "A lot of the research we do has global implications, and good contacts and communication are vital to the future success of our science." To tackle the challenges, Narayanaswamy and her colleagues at SAMS and other institutions in Scotland regularly work with other scientists from countries all over the world, sharing data, equipment and ship time to spread costs and help each other's research. But it is hard to achieve international agreement on how to control exploitation of deep sea resources.

The foundation for any advice on the control of the exploitation of deep sea resources is a sound 'mechanistic' understanding of how the deep sea ecosystem operates, including the physics, geology, chemistry and biology of the deep seas.

Fundamental research

The deep sea is the "inner space" of the biologically active part of the Earth, but largely because of the relative remoteness and technological challenges, fundamental research is still only "scratching the surface." A central challenge is to acquire an understanding of environmental variability across a vast range of time and space scales. Within this challenge, seafloor features of intermediate size deserve particular attention. Recent estimates by Paul Wessel and colleagues suggest there may be approximately 25 million abyssal hills, knolls and seamounts structuring the global seafloor.

Interview **Dr Bhavani Narayanaswamy & Dr Robert Turnewitsch**

Given this large number, the environmental influence of these topographic features is likely to be high. So far, however, there have only been very few systematic attempts to quantify how this influence manifests itself. One of Narayanaswamy's colleagues at SAMS, Dr Robert Turnewitsch, is fascinated with how ocean currents interact with these seafloor features and influence the formation of sediments and how this controls submarine landscapes and implications for organisms living in and on the seafloor. "It's important to understand how these hill- and seamount-controlled sediments are formed, as the underlying mechanisms will affect the distribution and nature of ecological 'niches' and therefore biodiversity," says Turnewitsch. "Work has been going on for decades in the area of sediment dynamics, but not much attention has been paid to medium-scale sea floor topography."

Turnewitsch studies the composition of the sediments and works with specialists in fluid dynamics and numerical modellers to analyse how sediments are formed. "The ocean flow has several components – for example, tidal and inertial ones – and some sedimentary deposits that were formed around submarine hills or seamounts may even help us to understand how certain aspects of deep-sea fluid dynamics may have varied in the past, and how this may have been interwoven with the overturning and mixing of the ocean and, therefore, climate change".

A mechanistic understanding of the deep sea environment is inherently interdisciplinary. Narayanaswamy works with Turnewitsch on various related projects, looking at the underlying biology. "If we did our biological research in complete isolation, we would struggle to interpret what our results were telling us," she explains. "For example, why is this animal living on only one side of a seamount? The answer may be more to do with ocean flow than any biological factor." It's all about "connectivity," says Narayanaswamy, who is interested in learning more about why the same species seem to exist over very wide areas, and studying the very subtle differences between them from one place to another – much as Darwin and others discovered variations in species in different locations on land. "If we can understand the controls on biodiversity," Narayanaswamy explains, "we can provide independent advice with regard to commercial activities, as well as with protection of the marine environment with the formation of Marine Protected Areas (MPAs). We need to protect these vulnerable habitats, but we also recognise the importance and benefit of the deep sea for society in general."

The deep sea has a wide range of resources for fishing as well as oil and gas exploration, and there are also ambitious plans to harvest precious minerals and tap novel energy sources, at depths greater than 2,000 metres and beyond. For example, hydrothermal vents are being eyed as good potential sources for sulphide deposits, and the sea floor on seamounts could also be a valuable source of ferro-manganese crusts rich in metals of economic interest. Amongst the other major issues are climate change, acidification and pollution. Long-term man-made damage (fishing is the single biggest culprit) is easier to measure at a regional or local level and at shallower depths, and some habitats are affected more than others, but the impact on the fauna of the deep sea is largely unknown.

All these problems added together may have a major impact on the biodiversity of the deep sea, but international waters are not easy to police. "A lot of crucial science is being done in the deep sea," says Narayanaswamy, but as quickly as the science progresses, so also does business see greater potential for profit and find better ways to exploit it. As a recent paper* explained: "One of the main problems that continue to cause concern is that the fastest movers in the deep sea are those who wish to use it as a service provider. Effective stewardship of deep sea resources will simultaneously require continued exploration, basic scientific research, monitoring and conservation measures."

Scientists are, however, gradually adding to their knowledge of the world's most mysterious region, to balance the competing interests involved, at the same time as advancing fundamental research. The scientific community also plays a key role in the drawing up of policy, providing guidance and identifying areas which need legislative protection.

> **"Effective stewardship of deep-sea resources will simultaneously require continued exploration, basic scientific research, monitoring and conservation measures"**

* *Man and the Last Great Wilderness: Human Impact on the Deep Sea*, PLOS ONE, August 01, 2011, by Eva Ramirez-Llodra, Paul A. Tyler, Maria C. Baker, Odd Aksel Bergstad, Malcolm R. Clark, Elva Escobar, Lisa A. Levin, Lenaick Menot, Ashley A. Rowden, Craig R. Smith and Cindy L. Van Dover.

According to Turnewitsch, industry, scientists and conservationists have common needs in the form of a sound functional understanding of the environment; and these needs will have to be served by continuing to do more basic studies, including curiosity-driven research.

Curiosity-driven research also often results in practical uses, not just for environmental conservation but also for the benefits of businesses and industry. "For example, without curiosity-driven research, one would not know that manganese nodules existed and where to look for them", Turnewitsch explains. "And only if we've gained a fundamental knowledge of how the deep sea works can we predict the effects of and guide any industrial-scale mining activities in the deep sea." This knowledge is still "embryonic," he adds, but any exploitation will have to take place "in parallel with our growing understanding of functional biodiversity," and the "natural collaboration" between industry and scientists will help to protect the deep-sea environment over the long term, combined with greater public awareness and official attention.

Narayanaswamy agrees that fundamental research is not a threat to commercial ambitions. In fact, it has important implications that could help to minimise damage to the environment and provide independent advice for commercial activities in the deep sea. According to Narayanaswamy, industry and scientists should work closely together to ensure that good background sampling and analysis of an area is undertaken, ideally before any exploitation activities begin – for example, there are already plans to start mining in the deep sea near Papua New Guinea, and more research would help to minimise possible environmental impacts. Whatever deep sea research is undertaken, Narayanaswamy feels very strongly that improved standardisation is needed when it comes to the methods used to analyse what's going on in the deep. For example, when environmental consultancies that are more often used to working in shallow-water environments offer their services to industry, they may not apply the same rules to their studies as deep sea researchers would.

Narayanaswamy explains this by describing how faunal samples are taken: "in shallow waters, you can use a 1mm sieve and find plenty of animals; in the deep sea, if you used a 1mm sieve, you would probably find very few, if any, animals, but if you used a finer mesh – say, 0.25mm – you'd get many more animals."

Moreover, it is not just the size of the mesh used for sieves, but also the way researchers provide potential new species with names that are not always consistent. There are numerous organisations and scientists undertaking biological research, but many of them are not taxonomists, i.e. those that identify and name new species. In many laboratories, new species are given a code that differs compared to a code used by another institution for what is possibly the same species. The problem is, with declining numbers of taxonomists and a potential increase in the number of new species being found, how do you make sure that all species are given the same code until they are properly identified?

"We're playing catch-up," says Narayanaswamy, "and it all comes back to networks between different countries and organisations, as well as the community of scientists." We also need more taxonomists to help with the classification of species, she adds. A scientist working in the north Atlantic may discover a "cosmopolitan" species which also lives in the Antarctic, but if the scientist is not familiar with the other region, how can we know it's the same species and map the distribution of species?

Without standardisation, it becomes incredibly difficult to undertake comparisons between different studies and laboratories.

As Turnewitsch comments, what we know about the deep sea is "only a drop in the ocean." Thanks to modern and evolving methods and technology, we are beginning to understand the functioning of the deep ocean, but the journey into "inner space" that started in the mid-19th century still has a long way to go – rising economic pressures making it more urgent than ever for the scientists to work more closely with industry, conservation organisations and policy makers to develop more effective and efficient ways to manage our deep sea resources and threats to deep sea biodiversity. This collaboration will have to be based on innovative and targeted fundamental research.

Did you know?

1 The oceans cover 71% of the planet's surface (the sea floor covers 362 million square kilometres out of a total of 510 million square kilometres), with 50% of the water below 3,000 metres in depth and a mean depth of 3,800 metres.

2 The deepest ocean trenches are more than 10,000km deep, further down below the surface of the sea than the highest mountain ranges are above sea level – e.g., Mount Everest would fit inside the Marianas Trench in the western Pacific with a couple of kilometres to spare.

3 Only 5% of the deep sea floor has been explored and less than 0.01% of the deep sea floor (the equivalent of a few football fields) has been studied in detail.

4 The volume of the deep sea (or "pelagic" zone) is over one billion cubic kilometres.

5 Over 60% of the sea floor has less than 200 metres of sediment cover. In some regions, sediment cover amounts to several kilometres.

6 The Earth's crust in the deep sea is rarely more than 7km thick and hydrothermal vents on the sea floor, where water seeps into the ocean, can generate temperatures of more than 400 degrees Centigrade.

7 The Ocean Biogeographic Information System contained over 19.4 million records as of September 2009, but only 75,532 of these were from depths of more than 1,000 metres, or approximately 0.004% of the total.

Interview **Dr Bhavani Narayanaswamy & Dr Robert Turnewitsch**

The role of MASTS

Narayanaswamy is the Principal Investigator in Deep Water Benthic Ecology at SAMS and also coordinator of the MASTS Deep Sea Forum. In her view, MASTS (the Marine Alliance for Science and Technology for Scotland) has stimulated deep sea research in a number of ways, encouraging collaboration and also improving access to funds. "Most of us had never sat down at the same table until last year," Narayanaswamy explains. "This means we are now working as a group under the MASTS umbrella to develop new proposals for research."

For example, MASTS researchers are trying to find funds for a new project in the northeast Atlantic to confirm the existence of a previously undiscovered cold seep – an area of sea bed which releases gas and other dissolved substances into the water, providing the conditions which allow many unusual species to feed and survive. This particular project will follow up on an initial discovery by Francis Neat and colleagues of Marine Scotland Science in 2011, when he collected rare clams in the northeast Atlantic that are normally only found in chemosynthetic environments – i.e., settings in which organisms do not fully rely on photosynthetically (plant-) produced food). The scientists don't know the exact location of the seep yet but, theoretically, seeps may occur every ~ 100km along the Atlantic margin. This is also a good example of a multi-disciplinary initiative, says Narayanaswamy, which will add to our knowledge of these unusual habitats.

Turnewitsch says that MASTS "facilitates and formalises interconnections between people," as well as makes it easier to fund new research. On the opposite side of the world, he is currently doing research on samples from the Tonga Trench in the western Pacific, the second-deepest point in the ocean at almost 11,000 metres. "Because of technological challenges, we still only know very little about these so-called 'hadal' trenches," says Turnewitsch, "so any sample we can get makes a huge difference." MASTS helped to fund the shipping of special equipment to the Tonga Trench which made this work possible, and will do the same for the project in the northeast Atlantic.

The 'seed' funding provided by MASTS facilitates proof-of-concept and other smaller studies and results in research output that can then be used to bid for funding for large projects.

MASTS researchers have access to a variety of state-of-the-art equipment, some of which has been specifically designed by MASTS researchers. Examples are the ultra-deep free-falling benthic lander systems designed by Dr. Alan Jamieson (OceanLab) to operate and sample in the deepest parts of the world's oceans. The challenge of conducting research in these extreme environments means that much of the science is, by definition, cutting edge. Use of modern technology, together with practical ingenuity is leading to novel discoveries including species and ecosystems new to science.

According to Narayanaswamy, the forum over the next couple of years will hope to focus more on the following issues:

1 Undertake research into cold-seep connectivity in the northeast Atlantic.

2 Intermediate-scale sea floor features (hills, knolls, seamounts, canyons, fracture-zone valleys and hadal trenches) are a major research theme because so little is known about their effects on biology, biogeochemistry, physical oceanography and interpretation of sedimentary palaeorecords of past environmental change.

3 Map and describe areas of suspected vulnerable marine ecosystems (VMEs). A total ban on deep-water trawling would not be universally welcomed, but there is widespread agreement that when VMEs are discovered, they should be closed to fishing. Habitat-suitability models are still not well enough defined to be of use to management, so more research is needed – whatever the cost.

4 Ocean acidification – are we going to see major shifts in the vertical zonation of the deep sea as the saturation state horizon shifts? How will we measure this? How will this interact with rising temperatures and spreading zones of low and decreasing concentrations of dissolved oxygen?

5 "Standardisation" – collecting, processing and identifying new species, according to internationally agreed parameters. "If this isn't tackled," says Narayanaswamy, "there is no chance of doing any monitoring work anywhere."

The deep sea forum

Scotland has a vast deep sea area stretching out to the 200 nautical mile boundary, encompassing a range of diverse habitats as well as key economic resources such as fishing, oil and gas. In addition to scientific interest in the deep sea, policy makers are required to protect many of these poorly-understood habitats and the often fragile ecology and biodiversity that they support. Increasing access to deep sea habitats and exposure through various media has also stimulated significant public curiosity in the life found in these deep, cold, dark environments.

The MASTS deep sea forum was set up in 2012 with the following aims:

1 Interact with the different communities with an interest in the deep sea

2 Engage with new partners and promote collaboration across disciplines in order to further deep water research both at a national level as well as internationally

3 Ensure greater integration between researchers investigating deep/shallow water and the climate/atmosphere

4 Discuss and help deliver the best scientific knowledge available to policy makers

The scientists in the deep sea forum believe that a more holistic approach to studying the deep sea is needed, bringing together researchers from a wide range of disciplines, including ecologists, chemists, physicists, modellers and climate scientists. They also need advanced technology that can operate remotely under extreme conditions.

PROFESSOR PAUL THOMPSON FRSE

Decision support for renewables

Scientists in Scotland are leading the way in researching the environmental impact of marine renewables – using Scotland's waters as a test-bed to study the long-term effects of the new generation of wind, wave and tidal technologies coming on-stream and helping to de-risk their future deployment...

Everyone would like to get energy out of the sea as cheaply as possible, causing as little damage as possible, but wave and tidal-stream technologies are in the early stages of development and we're only beginning to learn about their long-term impact on the natural environment. It may be relatively easy to calculate their physical impact on the ocean itself, but their complex effects on the physiology and behaviour of birds, fish and mammals are harder to predict – not just out of academic interest but also to address wider public concerns and avoid contravening international laws.

Environmental scientists in Scotland are ready to get down to business and keen to see more marine renewables being deployed. "Five years ago, we didn't have the tools required to measure their environmental impact," says Dr Ben Wilson of SAMS (the Scottish Association for Marine Science). "Nothing 'off the shelf' worked, so we had to develop our own tools, and now we need to get more devices into the water – not just a few demonstration machines but working arrays."

Getting data from the real world is a major challenge facing researchers, as the industry gathers momentum. According to Dr Ruairi Maciver of Lews Castle College, who models the "physical processes of the ocean," there isn't enough data in the regions of interest: "Ideally we'd have ten years of field measurements at a particular site to calibrate our models, but we have to rely on a handful of shorter periods, often at a different location. Developers need to protect their interests and are cautious about releasing data, so we have to work with what is in the public domain."

Professor Paul Thompson of the University of the Aberdeen adds that "the world will never be as perfectly described as we would like it," and that we already have significant data, despite the fact the industry is still embryonic. He also points out that the wave and tidal-stream industry is much less mature than the wind industry in terms of engineering viability and economics, as well as more diverse in terms of competing designs – and no-one has made any money yet from their investment. But scientists are making rapid progress in gathering data and piecing together the environmental jigsaw, in collaboration with developers and other bodies. A few years ago, says Thompson, it was difficult for scientists to persuade industry and regulators that it was in everyone's interests to pool their resources, but "we are getting there," he adds.

Scotland the test bed

These may be early days for wave and tidal power, and these schemes may never fulfil their potential, but the number of offshore wind turbines installed in the waters around the UK, and the wide range of new wave and tidal machines being tested in locations such as Scotland's Pentland Firth, will increase significantly over the next few years. Predicting their effect on the environment, however, is complex. It may be possible to model the hydrodynamics (the waves and currents, etc.) and also map the whereabouts of mammal, bird and fish populations (including their migration cycles and habitats), but nothing beats a study in the real world. And according to Thompson, Scotland is well placed to take the initiative in such a project, and also have an international impact.

"Getting baseline data from lots of individual sites is not the answer," says Thompson. "That is spreading ourselves much too thinly. We need to be more strategic and identify a few key demonstration sites (e.g. the Pentland Firth) where we can do much more in-depth research, pooling our resources to answer key questions about the longer-term ecological impact." This research could be coordinated with parallel studies – for example, in the Pacific – to compare results and try to reach some general conclusions. We also need to ask specific questions as soon as the devices are put in the water, says Dr Beth Scott, a senior lecturer from the University of Aberdeen – for example, "is there a predictable pattern to where species are most active in the water column to predict accurate risks of collision?"

The growing international interest in Scotland's marine renewables sector is reflected in the number of overseas delegates coming to the Environmental Interactions of Marine Renewable (EIMR) Energy Technology Conference in Stornoway from April 28 to May 2, 2014. "Scotland is the focus of the wave and tidal industry," says Thompson, "and we're also ahead in research into deep-water wind farms."

Even though environmental scientists have personal opinions on the issues involved, their primary job is to ask the right questions and gather the evidence needed to inform the debate. As the EIMR conference states in its programme, "the main objective is to bring together people from different disciplines and cultures to encourage collaboration and development of ideas," and the ultimate aim is to "yield positive outcomes for all" – i.e., not just the government and public but also the investors and developers, as well as the planet itself.

"We're looking at the long-term cumulative impact of putting these devices in the sea," says Hastie, "but what about the long-term impact of not putting them in?"

"Even though environmental scientists have personal opinions on the issues involved, their primary job is to ask the right questions and gather the evidence needed to inform the debate"

The human factor

The effects of human activities on marine mammal, seabird and fish populations have clearly increased through the years, but natural changes in environmental conditions also affect different species, and this has to be disentangled from man-made effects. Scientists are also concerned about the effects of renewables throughout the food chain, and understanding the underlying ecology, rather than focusing on isolated incidents.

As well as being careful when it comes to the science, researchers have to be aware of the complex politics involved in the energy business. An "army of consultants" are involved in environmental impact assessments, but there are still a lot of "unknown scientific issues," says Wilson, and everyone is having to learn very quickly as the industry grows. "As soon as a device goes in the water," he adds, "the lawyers show up."

Marine scientists are keen to partner with developers, but most of the early investment goes to prove the technical and economic viability of devices, rather than gathering data on possible environmental impact. The environment is "left until the later stages of development," says Maciver. "We know where to focus now," Wilson adds, "but there are many economic constraints and the timetabling must be pragmatic so we can tool up to meet the challenge."

Wind energy is at a different stage in the cycle, says Thompson. Companies in this sector have already proved the basic technology works and have some degree of economic certainty, so environmental impact assessment is essential to future success, to optimise investments and also get planning consent – especially for larger-scale wind farms located in deep-water sites. Wind is currently also "a much bigger pie," Thompson adds, compared to much smaller scale tidal and wave.

The need for more data

Whether it is wind, wave or tidal renewables, everyone – including regulators – is hungry for data. However, according to Thompson and Scott, a lot of the baseline data collected by offshore developers cannot be used to ask broader scientific questions, and may be insufficient to undertake Environmental Impact Assessments. "Even though a lot of data has been collected, the variety of methods used and the lack of access to allow the raw data to be collated is hampering the ability for that data to be more useful," says Scott. There is a lot of information on the distribution and abundance of species, adds Thompson, but on its own this does not allow regulators to assess how different species will respond to the deployment of renewables. "The challenge is to get more realistic information and develop the right research programmes," adds Hastie.

Scott also says marine renewables present a different challenge to developers because "they think we scientists know it all already and they can't believe how much we don't know about the marine environment." The "connectivity of data" is also important. You may know where birds are at any one time, but you don't necessarily know which colony and therefore which population they are from unless you tag a lot of birds – for example, tagged birds from Fair Isle have been found to be feeding off Fraserburgh.

It has been suggested that the renewables industry is evolving so quickly that a shortage of good data is inevitable, but Thompson also points out that renewables is the "first major marine industry that has had to face this level of assessment."

"We need baseline data that describe the present situation, but we need to pose the right questions for assessing impact and then define consistent methodologies for answering those questions – and this may require new tools," says Maciver.

Maciver specialises in measuring and modelling "the physics of the sea," and stresses the importance of conducting both pre-deployment measurement studies, to identify the best sites, and then post-deployment studies, to assess the impact of renewables. "We can model many of the processes that occur in our inshore coastal waters," he says, "but it is not yet clear how to represent renewables in these tools."

Good or bad vibrations?

The potential impact of renewables is complex and involves multiple factors. For example, noise can be disturbing to marine life and moving parts in turbines can sometimes be fatal, but another subject where research is needed is the impact of vibration on the sea bed, during operation as well as construction. What if sand eels (food for seabirds) are disturbed by vibrations from turbines, responding as if they are under attack and exhausting themselves in the process? And are these vibrations any worse than the effects of a storm?

In addition, not all human interventions are bad for marine life – some animals are attracted to oil rigs or wind farms and thrive there. "You sometimes get a benefit you did not anticipate," says Scott – e.g., most renewables sites will also be *de facto* Marine Protected Areas because they will exclude the more physically disruptive fishing practices such as dredging. "We have to balance the environmental benefits and impacts," says Thompson.

"Everybody has an opportunity to learn now," he continues. "The data are not always perfect, but there are many ways that we can help the regulators and the industry develop the decision support tools they need. Twenty years from now, we don't want to look back and wish we had done more research."

The science may be relatively young in many ways, and all the big challenges still lie ahead, but scientists in Scotland can already claim several successes, apart from attracting international attention. For example, says Thompson, "Scotland is the first country to be able to consent deep-water offshore wind farms, confident they don't infringe EU directives, thanks to a massive collaboration between industry, government and academia, plus the consultants, working together to scope out the issues." The technology is proven and the industry is now ready to embark on large-scale commercial projects.

Wave and tidal energy developers still have to prove the technology works. But a new scheme in the Pentland Firth should help to accelerate progress, with six tidal turbines providing the opportunity to monitor environmental impact close up, by lowering a platform packed with instruments into the sea.

If the Pentland Firth and other marine sites in Scotland can also fulfil their potential, collaboration will be critical, with scientists, investors and developers, utility providers, government and regulators working in tune with the public to enable new technologies to come on-stream with minimal environmental impact.

For that to happen, government organisations such as Marine Scotland will also play a key role by funding research. "No-one can do this in isolation," says Hastie, "and one advantage we have in Scotland is that everyone knows each other."

Scientists now have a clear idea what to monitor and have also developed the tools they require. They can also be an "interface between the industry and regulators," says Thompson. What they need now is an action plan – and money to get on with it. The Scottish Government has made renewables a strategic priority and is funding research "more than most other countries," but when the industry starts putting more devices into the water, the scientists want to be ready to study their impact – and share their research with the world.

The panel

Dr Beth Scott is a Senior Lecturer in the School of Biological Sciences at the University of Aberdeen. As a marine ecologist, she is chiefly interested in "predator–prey interactions," modelling and simulating the behaviour of seabirds, including where and how they feed, and what will change when more marine renewable devices are deployed.

Research: Scott has a multi-disciplinary background in marine ecology and oceanography and her research investigates the functional linkages between fine-scale biophysical oceanographic processes and the specific characteristic of different marine habitats (i.e. small-scale turbulence at the edges of banks) where predator and prey species overlap (when and where transfer of energy up the food chain actually happens).

Research goals: This work helps to quantify the type of vertical habitat that seabirds and mammals like to use to capture their prey – e.g. fast and turbulent water. If we can quantify those values, we can develop physical models to predict what changes lots of turbines will cause to the water column, nearby and also miles downstream. This will help us to predict how much energy can be extracted before it may interfere with predators capturing prey.

Priorities: We need to know exactly how animals are capturing prey in these high-energy environments and understand how the introduction of turbines and wave machines will affect those interactions. To do this, we need instruments on the sea bed (such as upward- facing acoustic sonar) and around real machines that can capture second-by-second information on predator and prey movement. This information will also allow us to calculate collision risks and learn more about the environmental effects of large-scale developments, helping regulators be sure they can safely give licences, as well as lowering investment risks.

Dr Gordon Hastie is a Research Fellow at the University of St Andrews Sea Mammal Research Unit. His research interests focus on the potential impacts of human activities (including marine renewable devices, sonar, vessels and pile driving) on marine mammals. In particular, he is interested in how marine mammals use sound in their everyday lives to navigate, find prey and avoid predators, and how noise produced by man might affect this. To address these questions, he has used a range of novel research techniques, including tracking animals around tidal turbines using imaging sonar, or measuring movements of seals during the construction of an offshore wind farm using GPS tags that are attached to the animal's fur.

Dr Ruairi Maciver is a Research Fellow at Lews Castle College, University of the Highlands and Islands (UHI). His research interests are the hydrodynamics of coastal environments and the interactions with marine renewables.

Research: His knowledge of coastal flows has been developed through mathematical and physical modelling studies of the interaction between waves and currents, the evolution of turbulence, and the forces experienced by structures located in such flows. He is applying this knowledge to the marine renewables sector to quantify the flow characteristics in the presence of marine renewable energy devices. Understanding how devices influence the physical environment is a key aspect of predicting how marine renewable energy developments will affect the biological environment.

Priorities: A campaign of flow-field measurements in regions that will host the first arrays of devices must be undertaken before and after deployment. Numerical models are powerful tools that can evaluate many scenarios. However, to ensure confidence in their output, they must be calibrated and validated against measurement. Establishing accurate and properly calibrated models will permit regulatory bodies to assess the environmental impact of future developments with confidence.

Dr Ben Wilson is a Senior Lecturer and Principal Investigator in Mammalogy and Marine Renewables at SAMS (the Scottish Association for Marine Science) in Oban, and a Marine Energy Theme Leader at MASTS. He is interested in the impact of marine renewables on marine mammals, and "what it's like to be predator and prey in these highly energetic and challenging habitats."

Research: Wilson's work focuses on developing tools and methods to work in high-energy marine environments. Before renewables came along, most researchers would avoid such energetic seas, but now there is a real need take the plunge, he says. Some monitoring methods can simply be applied with modification, whilst others need to be completely rethought/redesigned and tested to destruction. Using these tools, his team is beginning to uncover just how species such as porpoises are exploiting these dynamic spots.

Priorities: With the impending deployment of energy devices into our most energetic coastal waters, there's an urgent need to understand why large predators are already using these areas and how they might interact with our industrial activities. If there are conflicts, we will need to understand them before we can fix them, so properly monitoring what goes on around the first marine devices is vital.

Professor Paul Thompson is Head of the University of Aberdeen's Lighthouse Field Station in Cromarty. He is a population ecologist, using long-term individual-based studies to explore how environmental variation influences the behaviour, physiology and dynamics of marine mammal and seabird populations.

Research: These long-term studies have provided unique opportunities for research on interactions between offshore energy developments and marine mammal populations. Recent work has focused on understanding responses to underwater noise, and developing assessment frameworks that have been used to support consenting decisions for offshore wind farms.

Priorities: The longer-term population consequences of behavioural disturbance remain extremely uncertain. Consequently, assessment frameworks have had to be based upon a number of critical assumptions, particularly those linking an individual's exposure to noise with subsequent changes in reproduction or survival. Focused research around the next generation of large-scale developments is now required to test these assumptions. This should be underpinned by individual-based studies, which will allow the importance of these man-made stressors to be assessed in relation to the broader suite of drivers that can shape population dynamics.

Interview **Professor Nick Hanley & Dr Meriwether Wilson**

The politics of policy

The marine environment is one of the most complex and mysterious places on Earth, and human beings have a major impact on the state of the oceans and the health of the flora and fauna that inhabit the depths – not just through pollution and carbon emissions, fisheries and energy projects (renewables as well as oil and gas), but also government policies...

"Policy making is a messy, sometimes chaotic, process because it needs to include social, electoral, ethical, cultural, practical, legal and economic considerations in addition to scientific evidence," wrote Professor Ian Boyd – Chief Scientific Adviser to the UK Department of Environment, Food and Rural Affairs (Defra), and Professor of Biology at the University of St Andrews – in a recent article in eLIFE.

Marine scientists (including biologists and ecologists), environmental economists and scientific advisers are under increasing pressure to rise to the policy challenge. There are many stakeholders involved. Lots of people are worried about issues such as climate change (rising sea levels and acidification, etc.), water quality and declining fish populations, whilst the fishing industry wants fishing quotas relaxed. The oil and gas industry wants to exploit more hard-to-access resources, whilst renewables firms want to install more offshore wind turbines, as well as wave and tidal energy systems. There are also many questions. What is the value of the natural environment and marine resources? Should we focus on protecting rare species or relatively common species such as cod? What about protecting "normal" habitats which may be ignored because they are so common? And Government (including the planning authorities) must try to answer all of these questions and balance all of these interests, relying on the scientists for evidence and for advice.

Interview **Professor Nick Hanley & Dr Meriwether Wilson**

THE COAST IS ONE OF SCOTLAND'S GREATEST NATURAL RESOURCES

The major issues facing the policy makers include:

1 The designation of marine protected areas (e.g. cold-water coral reefs) – where, what restrictions, costs and benefits.
2 Marine energy – where to site renewables.
3 Bathing waters – how to implement tougher quality standards.
4 The marine strategy framework directive – how to protect resources.
5 Invasive species – understanding and managing pathways to invasion; e.g., via ships and platforms which can be "stepping stones" for migrating species, and "range-shifting" species which migrate as sea temperatures change.
6 Fisheries – a complex political issue because of competing interests (environmentalists versus industry) and the different levels of government involved (Scottish, UK, EU and trans-boundary organisations).

In addition, scientists are growing more concerned about rising sea levels and the need to update policies on flood management – and prepare for the future. This requires cost-benefit analysis of 'soft' flood defences (e.g., salt marshes and mud flats) versus 'hard' flood defences (e.g., dykes and walls). There is also concern about huge swings in seabird populations over the last 30 years – e.g., the decline in kittiwakes in the Firth of Forth. Is the problem caused by lower numbers of sand eels, or is it an unexpected consequence of improved water quality measures? And what can we do about it? Another issue attracting more attention in Scotland is the status of our "isolated" or vulnerable coast – places which are not yet protected but where human activity and populations are rising. Should we protect them from development?

Sometimes, the science can be ahead of policy and therefore help to shape the future approach. At other times, the science has to follow in the wake of decisions, but can monitor the results so policies can be modified accordingly. Sometimes, policy can reinforce positive or negative situations, and create problems as well as solve them. There can also be "ripple effects" which take everyone by surprise.

Scientists and policy makers sometimes disagree with each other, but scientists can also disagree amongst themselves, whilst economics adds a further level of complexity. Most funding in the past was directed at so-called blue-sky research, but applied research is getting more attention every year, taking economic value into account more than ever before, along with ecological concerns. "There used to be a bias against applied work," says Dr Meriwether Wilson, Lecturer in Marine Science and Policy at the University of Edinburgh, "but now we need answers – we have to prove we make a difference, and we must demonstrate impact."

According to Wilson, economics has helped to depoliticise and demystify a lot of the debate about policy matters, by providing "tangible equations" which help to persuade policy makers to do "the right thing." For example, studies have measured the impact of placing wind farms 1km offshore compared to 5km, thus providing a benchmark for future developments. Wilson also thinks that some developments (e.g., offshore wind farms) present us with many unknowns – will they be good or bad for the environment? – but that considering other factors such as visual amenity can help to steer decisions in the right direction. "The science can be well behind the policy questions," she adds, but at least when the structures are built, scientists can observe what happens, and the environmental impact on marine life also has to take account of the potential benefits of renewable energy, compared to the alternatives.

Most funding in the past was directed at so-called blue-sky research, but applied research is getting more attention every year, taking economic value into account more than ever before, along with ecological concerns.

Cost-benefit analysis is now used more widely in making decisions about the environment, and the environment itself is now regarded as an asset. Professor Nick Hanley, the MASTS Coastal Zone Forum Convenor and Professor of Economics at the University of Stirling, explains that 50 years ago, planners simply looked at basic factors such as the cost of a project and the value of what it produces (e.g., a hydroelectric power station). Conservationists were largely ignored. Nowadays, however, doing impact analysis and placing a value on the environment (e.g., wetlands) help to make better decisions. And by considering the economic and environmental factors, says Wilson, "we have moved away from the development versus conservation paradigm to a more open concept that allows deep evaluation by economists."

"If you ignore the costs and benefits of government policy," Hanley continues, "you can make some really bad mistakes."

Wilson sees policy as "a dynamic and influential process, an axis of alignment between social expectation, what resources can deliver and ensuring that the ecosystem is not degraded or over-used" in the process. Policy is also multi-scalar, says Wilson, because it involves local authorities as well as the Scottish Government, the UK Government and international bodies, and this means that policies sometimes match the scale and sometimes do not. "Policies can be very powerful and positive alignment tools but they can't always address the full spatial and temporal scale of actions over time," she adds. "The science part may have a biophysical expression, whilst the policy might exaggerate the decline in fish populations or encourage a reduced take."

Is the marine environment more complex to deal with in policy terms than the terrestrial environment? There are some parallels, says Wilson, between watershed management and marine management (in terms of trans-boundary systems), but the issues are "multidimensional" as you move out from the shallows to the deep sea. You also have to factor in current dynamics, multiple species and multiple environmental spheres. "The policies are dynamic and the environments are also dynamic," she says. "It is hard to get perfect alignment, coming from the more two-dimensional terrestrial system (including coastal management) to the three-dimensional marine system, where you can't access, see or touch what's there. It's mysterious in magical ways, but also mysterious in terms of actual knowledge, so we are also very dependent on technology such as remote sensors. We now have a better visual cognisance of marine systems, but a lack of tangibility and understanding affects our policy biases."

Hanley was brought in by MASTS five years ago to apply his economic techniques to the wider marine environment. Before then, he "never went into the sea." Bioeconomic modelling in the past was largely limited to fisheries, and this "drove the conversation between biologists and economists," but Hanley thinks that the methods used for the terrestrial environment translate very easily into the ocean. "Hardly anything is different, conceptually, anyway," says Hanley, "apart from the deep sea. How we think about combining ecological and economic modelling, and how we think about the economic consequences of the way in which biodiversity responds, is the same. The thought processes are identical – asking who will gain and who will lose. The deep sea is like outer space, and almost as inaccessible; but we are starting to make progress in applying combined ecological–economic thinking to deep sea management issues." Wilson says there are also different stakeholders involved but agrees that the process is largely the same.

The marine environment is also not completely strange, says Hanley, because people notice when they get sick after swimming or don't catch any fish. "They are well informed about the coastal area but not the deep sea – for example, it is hard to persuade people that we should protect cold-water coral reefs 200 metres down." Wilson adds that this is when the "magical factor" can influence public opinion, by showing the intrinsic value of marine life – for example, how coral reefs are just as important as the rainforests, and how destroying one thing can affect other links in the chain. "Economics can also be the saviour," says Wilson, because it quantifies resources.

> **The deep sea is like outer Space, and almost as inaccessible: but we are starting to make progress in applying combined ecological-economic thinking to deep sea management issues.**

Marine biologists and economists are working much closer together today to address all these issues. The renewables industry is raising new questions and the technology has greatly advanced, but the major difference in government attitudes over the years, according to both Wilson and Hanley, is a culture change – a recognition that we need more economic evidence, as well as scientific evidence, to make good policy decisions. There is more focus on the marine environment, but strategic impact assessment is now an integral part of the process; not just looking at short-term effects but thinking ahead 25 years from now, to consider the cumulative impact of multiple projects "in time and space" – an area where science can really contribute, says Wilson.

The Marine Alliance for Science and Technology for Scotland (MASTS) is not just an influence on policy but also a product of policy in the first place, created in 2008. "MASTS has opened up communications channels between the scientific and the policy community, as well as between universities," says Hanley. "One major benefit has been to bring in more marine scientists to Scottish universities, working in multiple disciplines, and this creates an opportunity for scientists who used to work in comparative isolation to work much more closely together, and encourages a partnership approach."

For Wilson, this also encourages more "joined-up thinking" and represents a philosophical shift, which means more dialogue and much more sharing of data. Ultimately, this could lead to greater economic efficiency, better science, better policy decisions – and a better environment for both humans and marine species.

The socio-economics of the sea

by Sam Anson (Head of the Marine Analytical Unit at the Scottish Government)

The one pre-requisite for socio-economics within marine policy, as with all science, is ensuring data availability of a sufficient quality – including spatial and temporal aspects – to provide robust, defensible evidence. This applies to all areas of policy, from marine planning to the Marine Strategy Framework Directive and to implementing Common Fisheries Policy reform. On a base level, this often means understanding the location and value of human activities, preferably with some view as to how these will alter over time. Becoming more analytical, it involves assessing drivers of behaviour and responses to change. Relevant examples would include the impact on tourism of offshore wind farms, or the nature of fisheries displacement following a Marine Protected Area designation.

Moving to a further scale of complexity, it is important that we understand the full range of benefits associated with environmental protection, including the value of ecosystem services. In a similar 'intangible' vein, we are interested in the indirect impacts of policy. For example, what changes might we observe in community structures and social outcomes as a result of any given policy change?

Of course, producing robust science is not an end in itself – it is also important for the science to have impact. Communication remains key on this front. First, to improve understanding of what economics can contribute: economics should illustrate how policy changes affect societal welfare (including jobs), and the trade-offs involved in any decision. When viewed this way, it is easier to understand its relevance to all policy decisions. Second, some of the methods that economists apply – for example, attempting to monetise aspects such as environmental preservation – do not sit comfortably with many from outside the discipline. Improved communication around the use of such techniques can help dispel any mistrust or scepticism.

Although socio-economics is now firmly entrenched within both the UK and Scottish marine science strategies, there is still more that could be done to raise its profile. It is heartening that the growing use of impact assessment and sustainability appraisal in recent years demonstrates the increasing demand for socio-economics as part of an integrated evidence base upon which to base decisions.

Interview **Professor Peter Tyack, Dr Mark Johnson & Dr Lars Boehme**

Researchers at the Scottish Oceans Institute Sea Mammals Research Unit in St Andrews are using smart technology mounted on marine mammals to understand their complex behaviour – and the impact of human activity on marine ecosystems.

It's a long way from bouncing around in a boat off the coast of Hawaii, lowering microphones into the sea, to sitting in his office in the east of Scotland 40 years later, analysing gigabytes of data from whales. It's also a long way from the surface of the ocean to the mysterious world 2,000 metres below where some whales hunt for food.

Professor Peter Tyack, who is now based in the Sea Mammals Research Unit (SMRU) of the Scottish Oceans Institute (SOI) in St Andrews, has always been fascinated with the sounds of whales and dolphins, but it has taken him several decades to make sense of their calls and songs and how they are affected by "acoustic fog" or ambient noise in the ocean.

To understand the scale of the problem, you have to consider that some whales only come to the surface five per cent of the time and spend the rest of their days in the depths where the Sun never shines. "You can hear them but you can't watch what they're doing," says Tyack. In addition, until very recently, not much was known about what goes on under the water. For example, it was only in the 1930s that scientists established that fish can hear, when Karl von Frisch taught catfish to respond to his whistling. In the 1940s, acoustic oceanography was starting to reveal the sounds of undersea animals, but it was not until the 1950s and 1960s that scientists were able to identify the sounds of many whale species. When Tyack was a student in the early 1970s (biology at Harvard then his PhD in Animal Behaviour at Rockefeller University), the science was still very basic. There were various theories about the behaviour of dolphins and whales, but hardly any evidence.

Tyack's early research focused on the songs of humpback whales. Whilst some of the team used a theodolite to follow the whales from the land, others did their best to follow on the water, using special underwater microphones to record the songs of males in search of females.

One of Tyack's main concerns over the years has been the effect of anthropogenic noise (sounds made by humans) on these undersea creatures. It has been estimated that since the beginning of the industrial age, ambient noise (e.g. from engines and propellers), has reduced the useful range of blue whale calls from about 1,000km to a current maximum of about 400km.

Interview **Professor Peter Tyack, Dr Mark Johnson & Dr Lars Boehme**

> **Protecting rare species is one thing, he says, but the research they do is equally important to the future of the fisheries and offshore energy industries, because all marine life is affected in some way by human activities.**

"To compensate for this," says Tyack, "whales sing louder and repeat the message more often. When faced with low-frequency noise, they also sometimes change from bass to tenor."

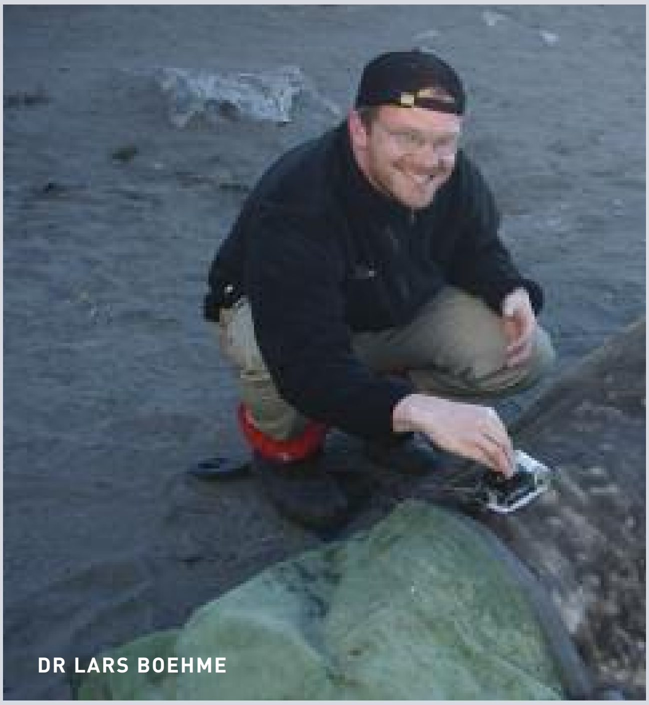
The problem caused by humans not only results in a change of behaviour, but can also endanger the whales, sometimes causing them to strand and die. Scientists started to think that sonar was the cause of the problem in the early 1990s, but it has taken almost 20 years to prove it.

Tyack has experimented with different acoustic technologies since the 1980s. One early project helped identify the individual "whistles" of dolphins. When two dolphins were in the same pool, and one of them called to the other, it was impossible to tell which one was making the noise by observing the dolphins. By fitting them with very basic microphones, however, Tyack was able to identify which dolphin made which whistle. This method allowed him to confirm that each dolphin produces an individually distinctive signature whistle, and to discover that they can imitate the signature of a partner.

The next challenge was to record sound and monitor other activities by sticking electronic tags on whales, seals and dolphins. Working at the Woods Hole Oceanographic Institution in Massachusetts, Tyack then teamed up with Dr Mark Johnson to develop more sophisticated devices, incorporating movement and orientation sensors as well as recorders – taking advantage of recent advances in mobile phone technology.

Johnson's introduction to biology was one night at a party, when a student told him all about a technical problem which Johnson believed he could solve – he has a PhD in Electronic Engineering from the University of Auckland in New Zealand. Soon he was "becoming a biologist," and today he's working next door to Tyack in St Andrews, where they collaborate with about 30 other researchers. Both Tyack and Johnson were brought to Scotland thanks to funding from MASTS (the Marine Alliance for Science and Technology for Scotland) as part of the programme to enhance marine capacity in Scotland.

"We not only carry out blue-sky research and study undersea mammal behaviour but also gather data which has real-world applications," says Tyack. Protecting rare species is one thing, he says, but the research they do is equally important to the future of the fisheries and offshore energy industries, because all marine life is affected in some way by human activities. The data which is gathered from various different devices (including those which measure temperature) can also be used as a proxy for measuring the impact of climate change and human interference with the marine environment. "Blue-sky research can uncover applied problems, and applied research can lead to blue-sky discoveries," adds Tyack.



DR LARS BOEHME

One example of applied research is studying how noise affects whales – e.g., naval sonar and the airguns used for seismic exploration. Because it is illegal to kill whales, and the US Navy had been blamed for a number of strandings in the late 1990s, it was important to establish whether or not naval sonar disrupted the normal behaviour of whales. In the year 2000, the US Navy ruled out all other factors in one mass stranding, and Tyack later demonstrated, using his new digital devices, that sonar did indeed trigger strong responses that could pose a risk of stranding. One technique involved emitting simulated sonar, then recording the response of the whales, and this year Tyack published a paper that "established the level of sound that started to disturb the behaviour of Blainville's beaked whales, helping to establish criteria for safe exposure."

Another practical problem is collision with ships. Why do whales sometimes appear not to hear ships? Should ships make more obvious sounds to warn marine mammals away? The answers may not just protect the mammals but also the ships.

Sometimes, the behaviour of the whales appears random, says Johnson, but when you analyse the data, a pattern emerges. "Whales are finely tuned systems," says Johnson, "and to understand the impact of ambient noise, you first have to understand normal behaviour."

Another recent project used passive acoustic data (listening for whale sounds) to estimate the population of undersea mammals – almost impossible and sometimes even dangerous if scientists rely on visual observations alone. And the results of this study may even be useful in assessing insect and bird populations, using similar statistical methods to analyse the data.

It is impossible, however, to disentangle curiosity-driven research from more obviously "practical" projects, says Tyack. In order to protect the different species, we first have to understand how they behave.

Smart technology

The underwater acoustic recording tags developed by Tyack and Johnson since they first teamed up in Massachusetts have improved significantly over the years – especially their memory capacity. Their collaboration resulted in the first widely-used sound recording tag for marine mammals, combining high-resolution acoustic and movement sensors, and the tags are now used worldwide. One major challenge, says Johnson, is that even though they may "work great on the bench," ultimately these very clever devices are stuck on animals which dive down to the bottom of the sea. They need to be extremely robust and small enough not to be noticed (the less invasive, the better), but the key challenge is integration, says Johnson.

The latest devices are capable of sampling very detailed data, recording the sounds of the whales as well as the sounds that the whales hear – not just the ambient noise in the ocean, but also echoes from the echolocation sounds emitted by whales to navigate and hunt. In addition, the new generation of tags is equipped with accelerometers, magnetometers and motion detectors which indicate the orientation of the whales and their direction of travel. Added together, this data allows them to reconstruct the "journey" of the whales over a period of a day or more – the limitation is the size of data storage on board.

As well as storage, battery and other equipment, will cameras ever be fitted? At the bottom of the deep ocean, there is not much to see and the images may not reveal much, says Tyack, "The key for understanding animal behaviour is to use sensors that match the sensory capabilities of the animals." When the tags come off the whales, flotation chambers take them back up to the surface where they send out a signal which enables the research team to locate and retrieve them, then download the data. By adding GPS, they would also be able to retrace the route of the whales more precisely.

Since he started developing tags to sample behaviour, Tyack has taken full advantage of advances in digital technology to drive his research. "If you can't solve a problem today," he explains, "just wait another six months."

Interview **Professor Peter Tyack, Dr Mark Johnson & Dr Lars Boehme**

Because data storage is limited (currently about 30Gb), researchers only get a very brief glimpse into life underwater and must prioritise what data to collect (e.g. which frequency range to detect). There is always a trade-off, says Johnson – especially between environmental and behavioural data. But according to Dr Lars Boehme, a MASTS Lecturer at the SOI who specialises in oceanography, "if you understand the habitat, you understand the species."

"The seals call home"

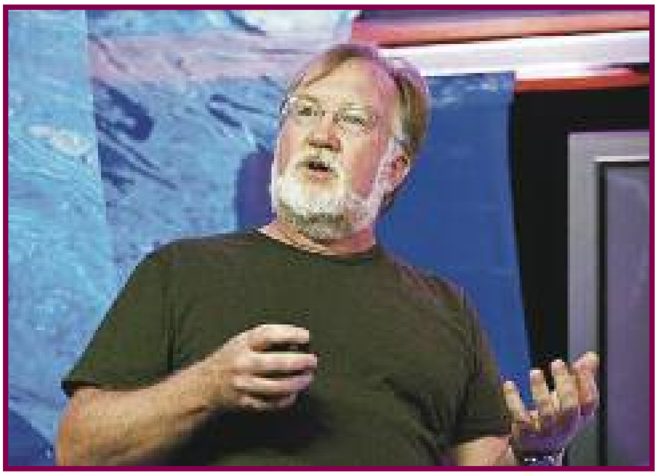
The SOI is also "making waves" in oceanography, using very similar tagging devices to map the oceans, using seals to carry the tags which send back a wide range of data, including temperature and evidence of photosynthetic plankton, as well as seal behaviour. Instead of waiting to retrieve the tags when they drop off, the researchers use satellites to pick up the signal in real time, whilst still attached to the host. There are two types of tags – one which uses satellite telemetry and another based on mobile phone technology, and every time they surface, "the seals call home," says Boehme. "It's like tweeting," he adds, because they only send back a few bits of data, compared to gigabytes on other devices.

The instruments used by Boehme measure salinity and temperature throughout the winter in the Antarctic, when it's almost impossible to gather the data because of the pack ice. According to Boehme, the devices also provide behavioural data which shows "the sensitivity of top predators to global and regional-scale climate variability." The data are also more detailed than anything gathered before. Over the last 150 years, he explains, scientists in the Antarctic got only about 13 temperature profiles from the southern Weddell Sea during the winter, but using seals – which dive under the ice to a depth of about 500 metres – produced about 2,500 profiles in a matter of weeks.

Interdependence

Other studies illustrate the interdependence of oceans and species. Boehme says that by studying the impact of climate variability on animals, it helps us understand the impact on ourselves, whilst Tyack describes their research as "not only a window on marine mammals but the ecosystem as a whole."

The work done by the oceanographers and marine mammal researchers at the SOI is a great example of how collaboration can be "greater than the sum of its parts," says Tyack. For example, he and Johnson work as a part of a team of about 30 people, including Boehme. In addition to biologists and electronics engineers, the team uses specialists in materials technology (salt water and electronics don't mix) and mechanical engineers, as well as statisticians, programmers and physicists. To some extent, says Boehme, he has "piggybacked" on marine mammal research, but the end result is data that are useful to everyone, and everyone also gets involved in analysing the data and designing the tags.



PROFESSOR PETER TYACK

For Tyack and Johnson, the specialisations of different team members are even more complex, and they rely on an extensive pool of scientists in Scotland and beyond. MASTS has also enabled them to move on from a world-class institution in the United States to an "amazing constellation" in St Andrews and a "synergistic network" of researchers in Scotland, functioning together in a way that no other country can offer, they say. "One of the main strengths of MASTS is its ability to attract international researchers," says Tyack. For Boehme, MASTS has also meant a huge change in direction. A physicist recruited by St Andrews seven years ago, he now has long-term funding and easier access to the other resources and people that MASTS has brought together at the SOI and other institutions in Scotland. "My focus has changed from next year's salary to good science," says Boehme.

The "good science" at the SOI will also have an impact far beyond its own walls. "What we are doing also matters to industry," Tyack explains. "We are developing new methodologies and new technologies that industry (e.g., fisheries, shipping and oil and gas companies) can use to analyse environmental impact. This is essential to protect marine life and to meet regulatory requirements. Some of the new monitoring technologies allow industry to operate when it would otherwise be prohibited, speeding up projects and saving tens of millions of pounds every year."

There is also a strategic "higher purpose," says Tyack, because their work is useful to environmental protection – in Scotland and beyond. "There is a disconnect between people's knowledge of environmental issues and the ocean," says Boehme, "but it is critical to see the connection."

Forty years ago, Tyack had a dream – to understand the behaviour of mammals which are out of sight most of the time. But by joining forces with other people, sharing data and being creative, his dream has begun to come true. "And now we have more dreams," says Tyack.

A new perspective on marine life

Why is a physicist involved in Scotland's most ambitious project to advance marine science? Why does he "sail the seven seas," analysing samples of water? And why does he want to send new spectral cameras hundreds of miles into Space to find out what is happening under the surface of the oceans below?

Dr David McKee describes his job as "measuring the colour of the sea." But this simple description disguises the fact that McKee is grappling with some highly complex scientific problems, using optical sensors to reveal what is happening in the marine environment – focusing on very tiny particles (including organic material and minerals) floating in the water, and ultimately building up a picture of the oceans which shows the carbon cycle in action and helps to monitor possible climate change.

McKee explains that he is trying to understand the ocean on a wide range of scales, from the microscopic to full ocean basins, using remote sensing data. The methods employed are very similar to those used in astronomy to analyse the properties of planets and stars by studying the light they emit. Sensors on satellites orbiting Earth are turned in the other direction to analyse the photons which reflect from the surface. By creating images at different colours (wavelengths), and removing the effects of the Earth's atmosphere, it is possible to build up maps of the materials that cause the colour of the ocean to change, including living organisms such as phytoplankton, as well as minerals and other dissolved materials. McKee also uses underwater optical sensors to observe how different particles respond to the light – e.g. absorption, fluorescence, reflectance and scattering, and can use this information to provide "ground truth" (or sea truth) for the remote sensing data. This is what McKee means when he says he "measures colour" to identify the particles in water.

To explain the different scales involved, McKee displays a time-lapse image of the "Blue Planet" built up from satellite data, showing photosynthesis on a planetary scale, then a picture of the microscopic phytoplankton so small we can't even see individual cells without using microscopes. Soon, says McKee, his research will go down even further to the sub-micron level, examining particles less than a millionth of a metre across. McKee's work also concentrates on "optically complex shelf seas" such as the Bristol Channel, Irish Sea and Mediterranean, where there is a lot of interaction between "natural" processes and anthropogenic activity – e.g., fish farms and fisheries, plus agricultural and industrial pollution from rivers.

McKee, a Senior Lecturer in the Department of Physics at the University of Strathclyde in Glasgow, explains that a lot of his work is concerned with "error correction" – helping to understand what's going on in the ocean by pointing out that often, things are not quite what they seem. For example, NASA satellites take pictures of the Earth which appear to show large areas of algal bloom around the Irish Sea, by detecting or "measuring" the colour of the chlorophyll. According to images produced using standard algorithms, these blooms seem to occur even in winter, when there's virtually no growth at all. Worse, they also suggest that there are permanent blooms in major estuaries that, if true, would suggest that the rivers were being heavily polluted with excess nutrients. But when McKee and other scientists go out in boats and take samples to measure the presence of algae in the real world, they discover that the real concentrations are much less than the remote sensing data suggests. The standard algorithms were designed for deep, clear oceans.

But not all the oceans are like that – in the sea around Scotland, sediments are kicked up by winds and tides, and there are natural inputs from rivers, as well as from agricultural, industrial and urban sources. The traditional algorithms are badly affected by the presence of suspended sediments in shallow coastal seas, so McKee and his research group have come up with new solutions which help to correct this misleading impression. To see the true picture, the algorithms have to be adjusted to accommodate these additional effects. Ideally, says McKee, for every remote sensing image he'd like to produce an accompanying map of error distributions that would act as a "health warning."

"It's all a question of perspective," says McKee. "There is a tendency to view satellite images as if they are maps, but what you see is not a map, it is a distribution of data points. And like all data, there are errors and we need to understand those errors and try to present them to users, so that they can get a better idea of what's really there."

The only way to solve this problem is by boarding a vessel and sampling the water *in situ*, then using the results to recalibrate or fine-tune the satellite data, making allowances for seasonal variations. McKee explains: "We understand the physics of how the signal is generated, and the optical significance of what we observe (scattering, absorption and reflectance), so we can change the algorithm accordingly." The raw data from the satellite sensors is exactly the same, but the way it is processed is different. But no matter how sophisticated the technology may become, there is no escape from field work in the real world below, determining "what's in the water."

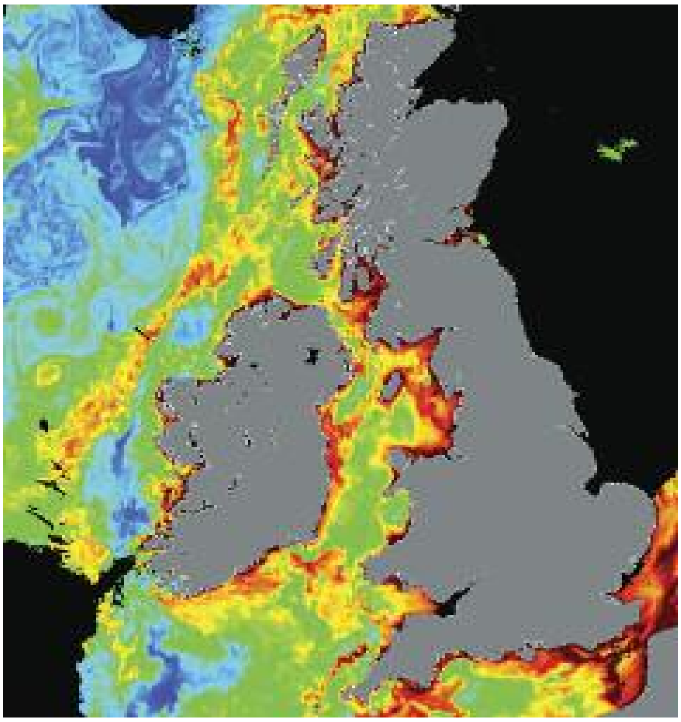
"But no matter how sophisticated the technology may become, there is no escape from field work in the real world below, determining "what's in the water.""

The technology evolves...

Whilst optical sensors have evolved through the years, so have the platforms they are deployed from, going from ship-based sampling water at depth and mounting the sensors on fixed moorings, to piggybacking on remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs), to using underwater "gliders" and remote-controlled aircraft and drones, as well as putting sensors in orbit – including the new generation of micro-satellites called CubeSats.

McKee is currently exploring how to work more closely with Glasgow-based CubeSat developer Clyde Space, and with other engineering and technology development groups in the central belt of Scotland. Whilst the big Space agencies still provide excellent data from conventional and massively expensive satellite systems, CubeSats offer the potential to expand the capabilities of sensors to entirely new levels, with "constellations of sensors" in Space sending back more data than ever before, using spectral cameras custom-built for dedicated tasks. "The images from NASA show one square kilometre per pixel," says McKee, "but we need much finer detail in order to monitor sea-lochs, rivers and lakes." Moreover, the CubeSat technology can be developed for a fraction of the cost of traditional spacecraft operations, opening the door to smaller organisations and nations taking on lead roles in Earth observation.

At the other end of the size scale, the group is starting to measure the optical properties of single cells and particles, using laser-based flow cytometry. This technology makes it possible to rapidly analyse thousands of particles per second, rather than laboriously counting them all one by one under a microscope. This will enable researchers to examine the whole population and analyse how different particles in the population interact with light and with each other. "This helps provide a context for the bulk optical measurements," McKee says. "The physicists are interested in how the particles affect the optical signals, while the biologists are researching their impact on the ecosystem."



SATELLITE DATA CAN BE MISLEADING

The research group

McKee and his colleague, Professor Alex Cunningham, run the Marine Optics and Remote Sensing Laboratory, which is part of the Biomolecular and Chemical Physics Group at the University of Strathclyde, using light "to interrogate and understand fundamental processes in nature." McKee and Cunningham focus on "radiance transfer in seawater, light utilisation by phytoplankton, optical monitoring of ecological processes, and remote sensing in the marine environment" – in other words, shining a light on what's going on under the sea. The laboratory has received more than £1.1 million in funding from the Natural Environment Research Council (NERC), the Marine Alliance for Science and Technology for Scotland (MASTS), the Scottish Government and the European Space Agency.

Current research undertaken by the laboratory includes:

- Ocean colour remote sensing for optically complex natural water systems;
- Monitoring physical–biogeochemical interactions from space;
- Effect of multiple scattering on optical signals in the marine environment.

Before MASTS came onto the scene about five years ago, McKee's research was funded by NERC and he was employed on a series of short-term contracts. MASTS funding helped to underwrite a Senior Lectureship at the University of Strathclyde that was awarded to McKee and provides significantly improved security of employment. "MASTS also provides an umbrella," he says, "that encourages collaboration and helps us to go for joint funding, as well as share resources, expertise and training opportunities." In McKee's view, MASTS also encourages communication between researchers from different disciplines, and enables them to tackle much more complex problems, because the joint expertise of the alliance is greater than the sum of its parts. "Now that MASTS is better established", says McKee, "it is starting to look at community projects that bring the broad range of expertise to bear on problems of national and international significance."

A good example of a project where MASTS brings different scientists together is recent research into the Mingulay cold-water coral reef, which was discovered in 2003 near the outer Hebrides. The "MASTS Dynamics and Properties of Marine Systems" theme is attempting to assemble an interdisciplinary research team to develop our understanding of this important ecosystem. This includes experts on the biology of the corals, and mathematical modellers who can predict the current flows that determine the availability of nutrition for the corals. McKee hopes to contribute to this effort by using his optical techniques to assess the nature of the particulate material that the corals feed on.

Although much of their research is fundamental and curiosity-driven, McKee and his group are also interested in the practical impact that their technology can have. This could take the form of assessing the local impact of aquaculture, or using remote sensing to understand the distribution of basking sharks and where they are feeding. There are also potential industrial applications, including pipeline monitoring and assessing the impact of offshore marine renewables. In many cases, the demand for information in other areas stimulates and shapes the development of technology.

Remote sensing gives his work an international dimension, says McKee, but MASTS "helps to reinforce and anchor a local focus," ensuring scientists make better use of the world-class expertise that is available closer to home. Sometimes, he adds, it's possible for scientists to go to international conferences, only to discover that the partners they need actually work in the same building; but MASTS ensures that more researchers are better aware of resources in Scotland.

Interview **Dr David McKee**

The collaborative ethos

McKee and his research group use optical sensors in orbit to show our planet breathing (there is as much photosynthesis going on in the sea as on land) and illuminate the impact of microscopic organisms that, added together, enable the planet to breathe, creating pictures which allow us to see at a glance what is happening across huge expanses of oceans – including what happens to carbon. But it is the collaboration with biologists, chemists and other disciplines, including areas such as economics and social sciences, that makes the research truly relevant to society.

"Physicists bring a very different perspective to marine science," says McKee, "and different ways of analysing problems. Our focus on a rigorous physical approach, including the demand for uncertainty estimation, provides potential end-user communities with a better idea of the true capabilities and practical limitations of our data sets. Ultimately it's the job of environmental scientists, such as ourselves, to provide better descriptions of the processes affecting the planet, to reduce the uncertainties in our models and to help decision makers understand the implications of future policies and actions." It may be complex and challenging science, but along the way, McKee says he is lucky enough to get the chance to be not just a physicist but also part biologist, geologist, ecologist and chemist. "Doing all this and getting to sail the seven seas – it ain't a bad life for a physicist," says McKee.

"Ultimately it's the job of environmental scientists, such as ourselves, to provide better descriptions of the processes affecting the planet, to reduce the uncertainties in our models and to help decision makers understand the implications of future policies and actions."

The bacteria that clean the deep blue sea

Whether it's hungry bacteria mopping up oil spills or microbes with unique properties that could be harnessed for biotechnological applications, Dr Tony Gutierrez is trying to understand the microbiology that drives different processes – research that could help to save billions of dollars or prevent a major environmental disaster...

Certain types of bacteria, found everywhere in the ocean, use oil as their main source of food. And if these bacteria did not exist, the surface of the ocean would be covered with a permanent oil slick, because so much oil enters the sea every year, as a result of both natural processes and human activities. However, when there is an oil spill as disastrous as the *Deepwater Horizon* incident, which occurred in the Gulf of Mexico on April 20, 2010, releasing an estimated 200 million gallons of crude oil over a period of 83 days, even the bacteria struggle to cope.

Oil exploration is now moving further offshore into much deeper waters in search of ever scarcer and more valuable resources. *Deepwater Horizon* blew up only a year after it had drilled the deepest oil well in history, and as the industry explores at greater depths, the costs of exploration and recovery increase all the time, as do the risks, with BP (which leased the rig) facing penalties that could reach tens of billions of dollars.

But what if we could speed up the removal of oil pollutants in the sea by feeding the ocean with "designer" micro-organisms that have improved oil-degrading capabilities, or by adding fertiliser that could stimulate the rate at which indigenous oil-degrading bacteria eat up the oil? Would that make it easier and cheaper to recover from disaster?

According to Dr Tony Gutierrez of Heriot-Watt University, we are still a long way away from a working "solution" for oil spills. But his research in recent years has started to uncover new information on the wide range of bacteria which "eat" or degrade oil, and understand the processes involved. Gutierrez was "in the right place, at the right time" when *Deepwater Horizon* blew up, working at the University of North Carolina in Chapel Hill, USA. The disaster may have been bad news for the oil industry and the environment, but it was also an opportunity for scientists to monitor, analyse and report the effects of a major spill. To understand what happened to the large volume of oil that had entered the Gulf and had not been recovered by BP or government task forces, a detailed microbiological investigation was carried out, which showed that the massive influx of oil into the Gulf had "triggered dramatic microbial community shifts."

Interview **Dr Tony Gutierrez**

Scientists investigating the microbial response to the *Deepwater Horizon* spill also observed a bloom of particular groups of bacteria in sea surface oil slicks and in deep waters (~1,000 – 1,300m depth) of the Gulf of Mexico, where much of the oil had become entrained. Some of the bacteria identified belong to taxonomic bacterial groups comprising members with known oil-degrading qualities – e.g. *Oceanospirillales* and *Cycloclasticus*. However, Gutierrez points out that molecular studies provide an indication of what these bacteria might be capable of doing, such as the types of carbon sources (e.g. hydrocarbons) that they can use as a food source. Other techniques are required in order to infer this with greater accuracy. "Identifying which bacteria played a major role in degrading the oil is an important step to understanding the complex nature of the Gulf of Mexico's response to the spill," says Gutierrez.

Using classical microbiological methods supported by a sophisticated DNA-based molecular biological technique called stable-isotope probing (DNA-SIP), Gutierrez and colleagues published their results in *The ISME Journal* in November 2013[1], which identified a number of bacterial species that contributed directly to degrading the oil in both sea surface oil slicks and in the deep waters of the Gulf. Their results provided incontrovertible evidence, that was hitherto lacking, on the hydrocarbon-degrading abilities of some of the most dominant bacteria that bloomed in response to the massive influx of oil into the Gulf; in turn revealing a "more complete understanding of their role in the fate of the oil." The oil-degrading bacteria identified included species affiliated to the genera *Cycloclasticus, Alteromonas, Pseudoalteromonas, Marinobacter* and *Halomonas*. A few months earlier, Gutierrez and colleagues published a paper in the journal *PLOS ONE*[2], which provided evidence that some of these oil-degrading bacteria had also helped to trigger the formation of large quantities of particulate organic matter (also known as "marine snow"), and additional results are due to be published this year. In addition to the formation of a very large oil plume that formed in the deep waters (~1,000 – 1,300m depth) of the Gulf, the copious quantities of marine snow that were observed floating on the surface of the sea and within the water column near the spill site, within just two weeks of the blow-out, was one of the other defining features of this historic spill.

Following this initial research and his recent move to Scotland, Gutierrez now focuses on "identifying new species of oil-degrading bacteria and their role in the removal of hydrocarbons from North Atlantic waters, whilst also continuing my work on the *Deepwater Horizon* oil spill with my colleagues in the United States and Europe."

"During the *Deepwater Horizon* spill, the Gulf of Mexico was like a massive laboratory experiment – the real McCoy. This provided us with a unique opportunity to get right in there at the heart of the spill and study the effects that the oil was having upon coastal, offshore and deep water ecosystems in the Gulf, as well as assess its capacity to recover."

Ultimately, this research will not only lead to a greater understanding of the natural remedial processes that unfold in the ocean during oil spills, and enable better planning before drilling starts, but also to improved methods for dealing with oil spills to minimise environmental impact.

Working in the lab, says Gutierrez, is rarely realistic enough to represent the complex and dynamic conditions found in the field. "During the *Deepwater Horizon* spill, the Gulf of Mexico was like a massive laboratory experiment – the real McCoy," says Gutierrez. "This provided us with a unique opportunity to get right in there at the heart of the spill and study the effects that the oil was having upon coastal, offshore and deep water ecosystems in the Gulf, as well as assess its capacity to recover."

Gutierrez also points out that the Gulf of Mexico spill was unprecedented with respect to the vast amounts of oil that had gushed out and the depth at which it occurred – approximately 1,500 metres below the surface, where water temperatures are no higher than 5°C and at high pressure. "It was a major perturbation, and we are still not there in terms of fully understanding its full impact on the Gulf. But one thing it highlighted was the importance for stakeholders such as funding councils, government and industry to invest more into research and technology to develop and optimise oil spill response contingency plans," says Gutierrez.

Gene sequencing has improved exponentially over the last ten years, says Gutierrez, enabling scientists to sequence thousands to millions of genes at a time, instead of tens or a couple of hundred. For example, new techniques have helped Gutierrez to identify entirely new species of bacteria. Another target is to study the functions of genes and how they evolved, and this understanding may eventually lead to practical solutions such as methods for dealing with oil spills. We know bacteria eat oil but "chucking bags of fertiliser into the sea" would not necessarily be an efficient response to an oil spill. "There is no single solution in sight," Gutierrez explains, but new advanced techniques are beginning to shed light on possible future approaches. "We are still only scratching the surface, however," he adds, "and the more we know, the more questions we ask."

1 Gutierrez, T., Singleton, D. R., Berry, D., Yang, T., Aitken, M. D. & Teske, A. 2013. Hydrocarbon-degrading bacteria enriched by the Deepwater Horizon oil spill identified by cultivation and DNA-SIP. *The ISME Journal* 7, 2091–2104 (November 2013). doi:10.1038/ismej.2013.98

2 Gutierrez, T., Berry, D., Yang, T., Mishamandani, S, McKay, L., Teske, A. & Aitken, M. D. 2013. Role of Bacterial Exopolysaccharides (EPS) in the Fate of the Oil Released during the Deepwater Horizon Oil Spill. *PLoS ONE* 8(6): e67717. doi:10.1371/journal.pone.0067717

The Scottish connection

Gutierrez graduated with a PhD in Microbiology & Immunology in 1999 from the University of New South Wales in Sydney, subsequently moving to the University of Florida for post-doctoral research experience. He then returned to Australia for a year before working in Scotland from 2003 to 2008 as a researcher at the Scottish Association for Marine Science (SAMS) in Oban. He spent the next three years working between the University of North Carolina at Chapel Hill and Lancaster University, before accepting his current position at Heriot-Watt University in Edinburgh in 2012 as Associate Professor of Microbiology, and successfully applying for funding from MASTS (the Marine Alliance for Science and Technology for Scotland).

As a microbiologist, Gutierrez is a specialist who offers different skills to MASTS, and is also in special demand because of his microbiological and molecular expertise, as well as his recent experience in the Gulf of Mexico and resultant research. His main collaborations until now have been with researchers in Australia, the USA and Europe, including a team in Vienna who are studying the microbiota of the human gut; but now that he is part of MASTS, new possibilities may arise in Scotland. Gutierrez has already started working with other groups that are a part of MASTS and is also involved in a new Doctoral Training Programme funded by NERC (the Natural Environment Research Council) that was awarded to Heriot-Watt as the lead partner to support over 85 PhD studentships in Oil & Gas research over the next 6–7 years.

The future of oil exploration

The work done by Gutierrez in the Gulf of Mexico may also have a major influence on future projects in the North Sea, where most oil exploration until now has taken place in waters less than 200 metres deep, as well as in other deep-water regions of the Atlantic. In the future, companies may seek to drill in water up to 3,000 metres deep. The rules of the game will be totally different and better methods of bioremediation will need to come into play.

Apart from trying to stem the worst effects of an oil spill, Gutierrez highlights three areas where microbial research could help in oil exploration:

1. Establish a "baseline" for the microbiology of the system before drilling and extraction of oil or gas begins, in order to provide a reference for the pre-spill "status quo" of the system.
2. During exploration, monitor the microbiology of the system and compare this to the baseline established in Stage 1, in order to detect any changes that might be indicative of contamination (e.g. oil leakage).
3. Develop a site-specific, targeted bioremediation strategy that could be used to enhance the activities of indigenous communities of oil-degrading bacteria in the event of a spill.

The implications of Gutierrez's research into oil-eating microbes go far beyond commercial or regulatory considerations, however, and his wider research interests also extend to other pollutants (e.g., microplastics and nanoparticles) and biotechnology. "Anyone with an interest to understand the natural environment must at some point in their research require to undertake a microbiological investigation, since microbes are quite often at the heart of how most things work in nature," he explains. "We are using techniques that cross disciplines," adds Gutierrez, but the major thrust of his research will continue to focus on what's going on in the sea, and the hungry bacteria feeding on oil.

Time for action?

In Scotland and around the world, the evidence for climate change is mounting all the time, and the sea is one of nature's best barometers. Marine ecologists in Scotland are not only helping to monitor the rate of climate change, but also trying to do something about it – and set the pace for similar research around the world.

The climate always changes (something called "natural variability") but according to the evidence, the rate of change in recent years has started to accelerate, and due to an increase in carbon emissions, temperatures are increasing and sea levels are rising. More frequent and more violent storms are starting to persuade the general public that climate change is really happening, but most marine ecologists are no longer debating whether or not the change is real but are trying to establish how fast it is accelerating and come up with a strategy to deal with it – or at least manage its impact in the future.

These were the conclusions of a recent panel discussion on climate change involving Dr Nick Kamenos of the University of Glasgow, Dr Natalie Hicks and Dr Henrik Stahl of SAMS (the Scottish Association for Marine Science) and Dr Heidi Burdett from the University of St Andrews, chaired by Professor David Paterson, Executive Director of MASTS (the Marine Alliance for Science and Technology for Scotland).

"We are more certain now that climate change is happening," says Stahl, "but there are still many questions to answer."

For Paterson, the evidence for climate change is becoming increasingly clear; rising sea levels are hard to ignore (a global average of 3 mm per year and an estimated 1.5 mm in Scotland), and increasing acidification of the sea (more carbon dioxide dissolved in the water). No single figure tells the full story, however. At the moment, global temperatures even appear to be falling, but this is just because they're on "the downward part of an upward trend" – in other words, the average is rising but in some years there is a temporary drop along the way. As Paterson puts it: "The climate is not the same thing as the weather." Also, the impacts will be very different across the globe, but Scotland will not be immune.

The Scottish marine context

Kamenos cites two examples of "wonderful" marine habitats in Scotland which are particularly vulnerable to physical and chemical damage: maerl (coralline red algae) and cold-water corals.

Maerl is an unusual type of algae which grows in shallow unpolluted waters. It grows very slowly (about a quarter of a millimetre a year) and plays a key role as an ecosystem service provider – a "kindergarten" for juvenile fish. This ecosystem would take thousands of years to recover from serious damage and this would mean not just a loss of habitat, but also a reduction in the fish population.

Corals are not confined to tropical water. Scotland has its own coral habitats and the full extent of the cold water coral mounds in the Atlantic was only recently recognised. Cold-water corals grow faster than maerl and cover very large areas. Like maerl, they also rely on producing hard calcareous coverings, and they also form important nurseries for fish. However, the coral beds are fragile and are easily damaged by physical disturbance (fisheries) or environmental changes (e.g. temperature, ocean acidification).

These sensitive maerl and coral habitats are not so well known in Scotland, but other anecdotal evidence of changing environmental conditions from more familiar habitats is increasing. For example, the shells of mussels being farmed on the west coast of Scotland are softer than in the past, making them more vulnerable to predators. This may be a response to climate change and, as water warms, other species (e.g., jellyfish, algae and invertebrates) may "invade" and displace the indigenous species, causing disruption of the natural ecosystem. This problem of invasive species is widely recognised but very difficult to manage, and some regions (the Clyde area, the Hebrides and Shetland) are developing "biosecurity" policies to manage the threat of these potential invaders.

However, a marine ecosystem is a highly complex network of interactions which are hard to fully understand and predict, and not all the news of climate change is bad news. Some species will be winners and others losers, says Hicks. For example, kelp (large brown algae) may become more abundant as the temperature rises, increasing coastal productivity and creating economic opportunities, but there are also dangers.

According to Burdett, the increase in sulphur gases (dimethylsulphide or the "smell of the sea") released into the atmosphere by algae, because of rising temperatures, forms clouds which help reduce warming – a paradoxical "knock-on" effect that has to be included in the scientific mix. The planet also has a "climate regulation mechanism" which keeps things in a state of equilibrium most of the time, but the evidence is mounting that human activity has "upset" this natural balance since the start of the industrial age. Says Paterson: "The engine of the Earth's biogeochemistry is bacterial metabolism, and after millennia of evolution we have reached the point where we may be superseding the bacteria as agents of climate change "

Maerl under threat from acidification?

By Nick Kamenos

Scotland's seas are home to a pink, plant-like organism called maerl, or coralline algae, that lays down a hard skeleton similar to corals. Each individual is the size of a tennis ball and many individuals are often found together in beds. Maerl beds form an important three-dimensional habitat on the sea floor, comparable to sea-grass beds in terms of their biodiversity. In addition to their role in maintaining high biodiversity, they are important in ecosystem service provision (e.g. acting as a nursery area for juvenile species) and play a large role in cycling and sequestering carbon at geological time scales. Indeed, some of the Scottish maerl beds may have been growing since the end of the last Ice Age, around 8,000 years ago. Whilst their hard skeleton allows them to perform important biogeochemical functions, it is also their Achilles heel – they only grow at a quarter of a millimetre per year and this makes them very sensitive to physical damage. There is uncertainty regarding how maerl beds will fare in warmer, more acidic waters; a key threat being ocean acidification, which may reduce the strength of their skeleton and lead to a breakdown in their three-dimensional structure. This could have devastating impacts on the services maerl beds provide, because any such damage would take centuries to regrow. Research is progressing to understand the sensitivity of these important systems to climate change.

What can we do?

It may be hard to get agreement on long-term solutions but "doing nothing is not an option" for scientists like Paterson. "There's much more we can do and much more we should do," he says. "In addition to raising awareness and basic measures like better transport and reducing our power consumption, we can adjust our fisheries policies (including eating different fish and better targeting of fish stocks) and plan to cope with rising sea levels by managing coastal defence more efficiently. We can also manage natural habitats, enhance marine environments and provide advice on the deployment of renewables."

According to Stahl, we can also create marine protected areas which give the ecosystems a chance to recover. "By saving relatively small areas," he says, "you can get huge economic benefits over the longer term." And the first step towards doing something about it is to fully understand what's going on.

Even if we stop polluting now and eliminate carbon emissions completely, the environment will continue to change, and some habitats may never recover. Paterson believes we are already past "the tipping point" and that a two-degree centigrade rise in global temperatures is unavoidable. Stahl is frustrated that "no-one wants to take the first step" in addressing the problem, despite the fact that measures such as carbon capture and storage (CCS) could reduce emissions by as much as 25%. "The technology is there but not the incentives," he says. "CCS could make a difference, but is seen as too expensive."

Public opinion

In coastal areas, it's possible to manage the impact of rising sea levels, but Burdett says the problem with the sea is "out of sight, out of mind," and that "the further you go out, the more uncertainties there are and the greyer international legislation becomes."

Hicks describes public opinion as "jaded" and thinks that all the "doom and gloom" of climate change discussion in the media can turn people off. She also wants to see more coverage of positive developments – for example, the fact that we know more and thus can avoid future problems, as well as the emergence of new industries such as seaweed-based products as a side-effect of temperature changes.

More "scientific" coverage would also raise the standard of public debate, drawing attention not just to the "hidden depths" of the ocean itself but also to the complexity of climate change. Personal experience can be misleading, says Paterson, particularly when people jump to conclusions after very hot summers or very cold winters.

"It's important to focus on what is most relevant to the general public and how a particular biogeochemical cycle relates to them personally," says Kamenos. "We should talk about resources like fishing and explain natural variability and the huge timescales involved."

Kamenos thinks drawing attention to rising sea levels is one of the best ways to demonstrate changes in climate, because they are something that everyone can see and relate to – especially if people are "hit in their wallets." If the Greenland ice sheet melts, sea levels will go up by 7-8 metres, but what makes people sit up and notice today is when insurance companies increase their premiums or even refuse to cover some homes because of the danger of flooding.

"We can never make precise predictions," Paterson adds, "but we can advise on how to adapt to the changes, to put in place the strategies and green measures needed. We can also help to re-create the habitats which are good at dealing with change – for example, mangrove swamps and salt marshes." and new technology will be a major part of the scientists' toolkit, whether it is used to implement physical measures or simply to help to monitor the rate of change so people can prepare for the worst.

> **"what makes people sit up and notice today is when insurance companies increase their premiums or even refuse to cover some homes because of the danger of flooding"**

Smart sensors

Top of most environmental scientists' wish list is the funding to set up a network of intelligent sensors that covers the globe, to monitor what's happening in coastal waters and the deep ocean. The sensors would be costly to install and maintain, but they would gather valuable data over the long term, which could be put in databases open to the public. One problem, however, is that governments operate in five-year cycles rather than the 30 – 40 years ecologists say they would need. According to Stahl, US researchers are already building large networks of sensors, but Europe has been slow to get going.

Instrumental data plays a critical role in understanding current and historical trends in the climate, but the picture is far from complete – e.g., baseline data for acidification. Ocean temperatures have only been measured in detail since the mid 1850s and Burdett says acidification is a "relatively recent problem" which has only been monitored for about the last decade. According to Hicks, we are "only starting to develop reliable sensors to measure pH and carbon dioxide," and new technology is needed. Scientists also need to know how to use "smart" devices and process the data. For example, says Paterson, "pH has weather" and varies through the day and in different locations – e.g., open ocean versus coastal systems and near CO_2 vents on the seabed.

Taking advantage of the latest technology, Hicks and her colleagues at SAMS have been conducting experiments to observe the effects of changes in temperature and levels of carbon on micro-organisms living in the mud; but sometimes this can feel like "taking one step forward, two steps back", as the results prove much more complex than expected. Stahl explains that sediments are carbon sinks and that it's important to understand the "potential feedback effects" as temperatures and carbon dioxide levels continue to rise, in coastal areas and the deep ocean. "Acidification may increase or decrease the ability of micro-organisms to process and sequester carbon," says Stahl, who is also concerned about hypoxia – when excess nitrogen and phosphorus feeds algal blooms which starve the sea of oxygen, killing marine life.

"This is one part of a much bigger puzzle," says Stahl. "And it's only by working together that we can prove that climate change is happening and address the many complex issues involved."

"No single piece of research can provide the whole answer," adds Kamenos, "and that is why government organisations analyse all the available literature to find common trends, examining different components of climate change over the long term." No computer model or reconstruction is perfect, he adds, but when hundreds of reports show ocean temperatures are rising, and instrumental data matches simulations, that tends to confirm the trend. For example, says Kamenos, when you model the climate based on "natural" factors alone (including variations caused by volcanic eruptions, etc.) and compare this with the instrumental data from the real world, there is a gap between the model and reality. When you add anthropogenic and natural factors together and compare this with the instrumental data, the figures match more closely – thus demonstrating that the climate is being affected by human activity.

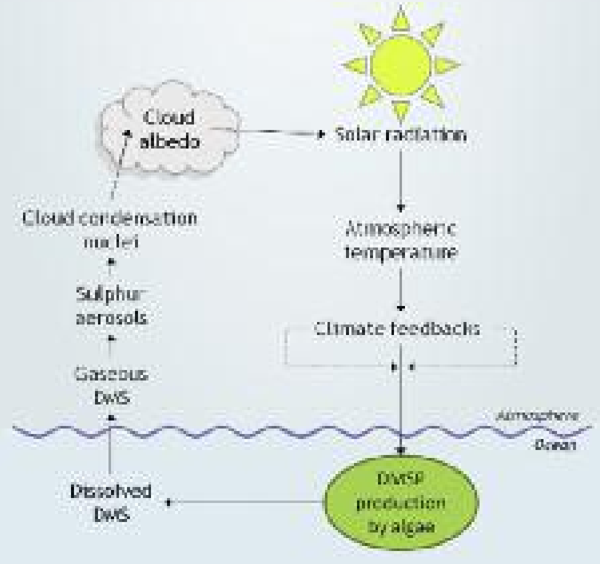
Making sense of the smell of the sea

by Heidi Burdett

Many of us know about the 'greenhouse effect,' which is being strengthened by increased emissions of greenhouse gases from human activities. However, there are other gases in the atmosphere, loosely referred to as 'anti-greenhouse gases,' which are involved in climate-regulation feedback systems and act as natural atmospheric thermostats. One of these gases is dimethylsulphide (DMS), and anyone who has been to the seaside will have breathed it in at some point, because it is one of the gases that make up the 'smell of the sea'.

DMS originates from sulphur compounds produced by most algae in the oceans, from coastal seaweeds to tiny single-celled algae called phytoplankton that float in the surface waters of the open ocean. Once in the atmosphere, the gas is oxidised into 'cloud condensation nuclei' – tiny sulphate particles that allow water droplets to cluster together. This promotes the formation and growth of clouds, limiting the amount of solar radiation reaching the Earth's surface. It is suggested that, as algal growth increases, DMS emissions and thus cloud cover increase, reducing surface temperatures. This in turn reduces algal growth, subsequent DMS emissions and cloud formation decline, increasing the temperature again, and so the cycle continues.

Feedback mechanisms such as this are composed of complex biological, chemical, physical and geological interactions that are sometimes not well understood. However, given their potential importance in regulating climate, climate scientists are now trying to understand how these processes will change in the future, as atmospheric CO_2 continues to increase.



Scotland the test bed?

The problem with ecology, according to ecologists, is not just the complexity but also the timescales involved, and natural variability can be confusing. For example, says Burdett, there are very large changes in carbon dioxide and oxygen levels in the vicinity of coral reefs over the course of a day, so you have to be careful how you measure and analyse data. Studying one factor in isolation may lead to certain conclusions, but as soon as you add other factors, the complexity increases exponentially. When you study the responses of an individual species, you also have to look at how it interacts with other species. Says Paterson: "We tend to think in terms of individual factors, but the real environment integrates everything – living organisms are affected by multiple factors." For example, when the temperature rises and the icecap melts, a "feedback mechanism" comes into play, which makes it harder to predict how much the ocean will expand. If you focus on what seems to be the single most damaging factor – e.g., carbon dioxide or nitrate or phosphate pollution – this can limit your perspective. "When you combine two different stressors, the effect is not just additive, but can be synergistic," says Paterson.

People think in terms of generations, and the shorter the timescale, the "noisier" the data may appear and the less people tend to believe any change is occurring. To solve this problem, scientists use proxies such as fossils, shells and sediments to recreate a model of the climate in the past and compare this with current conditions and trends, to demonstrate that change is really happening.

"We don't want to be backed into a corner," says Kamenos, "without any options. We can't sit back waiting for something to happen then think we can do things, like stopping pollution, and all will be fine. The climate system has a lot of inertia in it. Even if we stop emissions now, there's still a century of change ahead, and that's why it's important to do something now."

When it comes to climate change, the members of the panel say we need an holistic approach – for example, joining forces with economists and industry, as well as helping governments draw up new legislation. They also think that Scotland could become an international "marine laboratory" to monitor the rate of climate change and help develop strategies to mitigate adverse effects, with MASTS researchers playing a key role. The waters around Scotland's coast are a rich source of energy (oil and gas, wave, wind and tidal) and food (fish and seaweed, etc.), so whatever we can do to protect these resources and advance the sum of scientific knowledge would have a major impact on the economic future of the country, as well as the rest of the planet.

"Even if we stop emissions now, there's still a century of change ahead, and that's why it's important to do something now..."

The panel

Dr Henrik Stahl is a Principal Investigator in Marine Biogeochemistry at SAMS, where he has been based for the last seven years. His scientific work focuses on benthic mineralisation, with an emphasis on carbon and nitrogen cycling in coastal and deep-sea sediments. He is also particularly interested in sediment–animal relations, such as solute and particle transport induced by the macrofauna and the associated effects on the oxygen and pH dynamics in marine sediments, as well as the development and application of new microsensor technology.

Dr Nick Kamenos is an Honorary Lecturer in the School of Life Sciences and a Research Fellow in the School of Geographical and Earth Sciences at the University of Glasgow. He describes his background as "classic marine ecology," and says that he uses "biological techniques to answer geological questions and geological techniques to answer biological questions." He is interested in global change "from the perspective of marine calcifiers," as well as algae and coral, and the synergy between natural and anthropogenic change, using marine organisms as a proxy for climate change, with an emphasis on temperature, salinity and acidification, particularly in the North Atlantic.

Dr Natalie Hicks is a Post-Doctoral Research Associate in the Effects of Ocean Acidification on Benthic Biogeochemistry at SAMS, where she has worked for three years. Her research focuses on the effects of environmental change (including acidification and temperature) on marine benthic systems, with an emphasis on sediments and nutrient cycling. Her PhD (at the University of St Andrews) focused on "determining the effects of elevated CO_2 and temperature on benthic primary production under different macrofaunal diversity levels." Natalie says she is "excited" by mud and the complex effects of climate change on different organisms and the ecosystem, and is also interested in how ecologists and biogeochemists work together.

Dr Heidi Burdett is a MASTS Research Fellow based in the Department of Earth & Environmental Sciences at the University of St Andrews. A biogeochemist, she is currently doing research into sulphur gases (dimethylsulphide) and benthic habitats, particularly the carbon storage potential of coral and algae, as well as kelp forests and sea grass meadows, with an emphasis on "the link between ecosystem function and biogeochemical cycling in estuarine, coastal and marine environments, in response to both natural variability and projected changes in climate (e.g. ocean acidification and global warming)."

Professor David Paterson, of the Scottish Oceans Institute, School of Biology at the University of St Andrews, is the Executive Director of MASTS (the Marine Alliance for Science and Technology for Scotland). He has always been interested in "how biology and physics interact," and how organisms respond to the environment – and how they adapt and evolve. His work encompass the study of how biodiversity contributes towards ecosystem function and the provision of ecosystem services under different scenarios of climate change. Paterson's career has spanned a range of different attitudes to climate change in scientific circles, and he recalls how, in the early 1990s, his colleagues advised him not to mention the subject in a grant application because it was regarded as already "old hat."

FIGURE 1

Clear as mud

by Natalie Hicks

At first glance, a mudflat *(Figure1)* may not appear to be as charismatic or important as a coral reef, but you don't need to dig very deep to discover why these fine sediment habitats are so interesting. Marine sediments (sand and mud) cover a huge proportion of the sea bed, from deep sea to coastal regions, and provide a variety of important services, such as carbon sequestration and nutrient cycling.

FIGURE 2

Coastal mudflats and subtidal deposits thrive with varied communities of – often invisible – plant and animal life. These habitats cover vast areas and may seem uninhabited, since the organisms that live there are often small or buried and thus can't be seen with the naked eye. Where the deposits are shallow enough for light to reach the surface of the bed, there is energy for photosynthesis and there may be sea grasses growing or, more often, communities of microscopic algae. These are single celled organisms *(Figure 2)*, usually dominated by a group known as diatoms. Despite their small size, these microalgae can spread across large areas and contribute a significant proportion of the carbon and oxygen cycling. They provide food for other organisms, and even influence sediment erosion due to secretion of an organic material that acts like glue, protecting the bed against erosion.

FIGURE 3

Also living on top of and within the mud are many invertebrates *(Figure 3)* that feed on the microalgae. The movement of these burrowing organisms through the sediment stimulates the penetration and recycling of oxygen, carbon and nutrients. The rich diversity of invertebrates also attracts predators, such as fish and, in intertidal regions, large native and migrant wading bird populations.

FIGURE 4

Climate change pressures, such as increasing temperature, rising sea levels and elevated CO_2, are likely to cause changes to these muddy habitats, and affect the behaviour and occurrence of the organisms that live within them. As the 'meeting zone' of the atmospheric, terrestrial and marine systems, these habitats are also under extensive pressure from human activity. Scientists investigating the ecology of these habitats often spend long days sampling and taking measurements, and have learnt to work quickly enough to beat the incoming tide *(Figure 4)*. Knowledge gained through this research will be invaluable in deciding how best to manage these habitats under future environmental change.

Next time you pass an expanse of intertidal mud, take a second glance and see if you can spot any signs of this secret diversity – brownish or greenish patches indicate the presence of the microalgae, and small 'hills' or dents in the sediment surface are often the burrows of the invertebrates, in their 'secret' but important kingdom.

Aquaculture & Society

Fish farming: just add water and a drop of science

In the early 1970s, the Highlands & Islands Development Board (HIDB) speculated that salmon aquaculture would be a profitable but crofting-style activity producing a few thousand tonnes of fish a year. Today, the industry produces around 160,000 tonnes a year and has the ambition to produce 210,000 tonnes by the year 2020. The shellfish industry has also seen significant expansion over the same period and, although volumes are relatively low, there is an aspiration to double the size of this sector to 13,000 tonnes by 2020. And scientists in Scotland are playing a key role not only to improve production, but also to combat the threat of disease and monitor environmental impacts.

Aquaculture has become a mainstay of parts of Scotland's coastal economy, as the largest producer of farmed Atlantic salmon in the EU and third-largest globally alongside Norway and Chile. The Scottish industry is worth approximately £600 million at farm gate prices, accounting for over one-third by value of Scotland's food exports, with recent year-on-year increases of 5.6 per cent. In fact, farmed salmon ranks only second to whisky in terms of export value.

The industry also has wider social importance, especially in remote areas of the west coast and islands, where it provides an important source of local employment.

Today, the aquaculture industry in Scotland employs about 6,000 people and helps to underpin sustainable economic growth in many rural and coastal communities, particularly in the Highlands and Islands. Whilst the salmon industry is dominated by relatively few large multinational companies, other parts of the sector, such as trout and shellfish, are usually small privately-owned businesses.

More than 50 per cent of the world's seafood is now produced through aquaculture. Capture fishery production has plateaued at about 100 million tonnes and, even if fished sustainably, is unlikely to increase. Demand for seafood is increasing as a function of population growth and increases in *per capita* consumption – aquaculture will have to grow to meet this demand. But the issue is not just the basic provision of affordable protein – the world's growing middle class wants seafood that is safe and appetising and salmon is particularly valued.

Given the importance of the industry and the huge growth in global demand, the Scottish Government has agreed to support industry targets for aquaculture:

1. To increase fin fish production to 210,000 tonnes (from 164,380 tonnes in 2012)
2. To increase shellfish production to 13,000 tonnes (from 6,525 tonnes in 2012)

Aquaculture is a vibrant and increasingly important industry in terms of food security as well as the economy, and the Scottish Government has a "very positive" view of its future and is keen to engage with both the industry and the researchers who are driving the science and trying to ensure its sustainable growth.

Aquaculture is a vibrant and increasingly important industry in terms of food security as well as the economy, and the Scottish Government has a "very positive" view of its future and is keen to engage with both the industry and the researchers who are driving the science and trying to ensure its sustainable growth. With increasing funding to support aquaculture research emerging through the recently-approved Scottish Aquaculture Innovation Centre, the potential for specific aquaculture initiatives filtering through from the UK Research Councils and the prospect of significant investment in sectorally-relevant research through the EU's Horizon 2020 programme, the MASTS Sustainable Aquaculture Forum has been involved in developing a comprehensive research strategy designed to help focus and influence the allocation of these funds to agreed priority areas for research and innovation. The majority of Scotland's aquaculture-related research capacity comes together through MASTS. The Institute of Aquaculture at the University of Stirling is a recognised international centre of excellence for aquaculture. Other world-leading expertise in fish disease and immunology is based at the University of Aberdeen. Throughout the University of the Highlands and Islands network and at the Scottish Association for Marine Science (SAMS), there is a wide range of expertise in assessing and helping to mitigate the environmental impacts of aquaculture. St Andrews University has a focus on fish molecular genetics and interaction between aquaculture, seals and cetaceans. Edinburgh Napier and Heriot-Watt Universities also have specific interests in aquaculture. Marine Scotland Science (MSS) has tight links with all academic research institutions within MASTS through studentships and research fellowships, and carries out high-quality research across the full spectrum of subjects in relation to Scottish aquaculture, including epidemiology, pathogen and disease characterisation, host–pathogen interaction and immunology, and interactions between aquaculture and environment. MSS supports the Scottish Government by provision of highly-applied evidence-based research, consequently used to support relevant policies.

The domestication and intensification of any farming system will inevitably result in unintended impacts. The pace of aquaculture expansion over the last 30 years has been meteoric in comparison to established terrestrial agriculture, much of which has evolved over many hundreds of years. Disease is a particular challenge and the majority of the UK's research expenditure on aquaculture is focused in this area. For aquaculture, the UK maintains a very high health status within the EU, which maximises our potential to export our aquaculture products. But occasionally, as with every other form of animal and plant production, significant disease challenges emerge. Monitoring the health status of farmed fish and shellfish is a statutory responsibility of the Fish Health Inspectorate, which is based at the MSS Laboratory in Aberdeen. A close working relationship with MSS scientists and the wider aquaculture health and welfare-related science community helps to ensure that, for most diseases, we have the capacity to identify emergence, track their spread and suggest a range of treatments. However, the range of available fish medicines is limited and needs to be expanded, and fish vaccines in particular need to be developed for a range of pathogens. Imagine the difficulties of treating many thousands of fish, often in very difficult conditions, at sea. That is why we need treatments that are both efficacious and easy to administer.

In the past, outbreaks of the virus Infectious Salmon Anaemia (ISA) have had a devastating impact on the salmon industry – if detected, the stock must be destroyed. Maintaining high levels of biosecurity on farms is critical to preventing such infections occurring and spreading. ISA was responsible for reducing Chilean salmon production by a third a few years ago and it is only just recovering to previous production levels. Sea lice are a particular problem for some salmon farms. A naturally-occurring ectoparasite of Atlantic Salmon, sea lice can proliferate in farming situations, where they have large numbers of captive hosts. The industry is committed to minimising the numbers of lice infecting their farmed fish and a range of treatments and management measures have been developed, to maximise the welfare of the farmed fish and minimise any potential impact on wild migratory salmonids. However, the capacity of all pathogens to develop resistance to treatments means that farmers need a range of efficacious medicines which they can use to minimise the potential for disease resistance to develop. For sea lice, the hunt is on for new in-feed treatments, the development of biological controls using wrasse, which act as cleaner fish by picking off and eating the sea lice on farmed salmon, and – the holy grail – a vaccine. Selective breeding for resistance to a number of diseases is also progressing on a number of fronts.

State-of-the-art molecular biology is also being used to understand and investigate ways to cure diseases, combining this with integrated pest management to optimise the use of treatments and minimise the potential for disease to become established.

For many years, Scotland has been recognised internationally as a centre of expertise and training for aquaculture. The Institute of Aquaculture (in Stirling) and the University of Aberdeen in particular have generated a large number of graduates, MSc and PhD, who now work around the globe. Many have risen to senior positions in their respective countries and are keen to maintain links with the UK. Work conducted at SAMS, the University of St Andrews and MSS has fed directly into regulation of the aquaculture sector. Indeed, one of the underlying rationales for maintaining high levels of scientific expertise in this field is to ensure that the UK has a strong and authoritative voice in EU and wider international debates framing policy and legislation relevant to aquaculture. The UK leads many EU-funded research projects and plays an active role in driving and co-ordinating the aquaculture research agenda. Strong links with Norway, Ireland and Canada have resulted in collaborative research on fish disease. Scottish scientists also have an active presence in South America, notably Chile. Southeast Asia, with over 270 different species being produced through aquaculture, has been a fertile area for research and international students. Many of the economies in this region have moved from "developing" to "emerging" over the last 20 years – this status is now being recognised and the UK's recently-announced £375-million Newton Fund is specifically targeted at forging strong collaborative research links with these countries – many of which have important aquaculture sectors.

No silver bullet

One of the discussed topics concerning salmon aquaculture revolves around the naturally-occurring, endemic, native parasite – the sea (or salmon) louse. As its name suggests, it is found in sea water and feeds on the skin and mucous of salmon, which has been mooted as a possible selection pressure leading to leaping behaviour. The earliest known recordings of sea lice causing discomfort of salmon date from the writings of an 18th-Century Scandinavian bishop, whilst mortality events in Scotland were first depicted by Lewis in 1905. A year later, sea lice research was conducted in Aberdeen by an early predecessor to Marine Scotland.

Management of sea lice is a high priority for Scottish fish farmers, because if it is left unmanaged, farmed salmon health and welfare could be reduced. As such, an estimated £30–£40 million per year is spent by the sector in applying management methods such as: using veterinary medicines; coordinating production (such as stocking, fallowing and the use of single-age class cohorts); stocking cleaner fish as biological controls; recording lice counts for informing treatments; using functional feeds; and rotating medicine use to avoid resistance.

Sustainability and the future

Fish are one of the most efficient animals at converting their food into protein that humans will eat – outperforming chickens, sheep and cattle.

This is an important strategic issue in terms of food security, because some of the raw materials used in animal feeds may become limiting as the demand for food increases. For those forms of aquaculture that rely on raw materials such as fish meal and fish oil, sourcing alternatives has become the focus of significant research effort.

Fish oil is the main source of Omega 3 in our diets. Omega-3s are considered essential fatty acids, meaning that they cannot be synthesised by the human body. Although many of the health claims associated with consumption of Omega-3s remain controversial, they are implicated in helping to reduce the risk of some cancers, inflammation, cardiovascular disease and developmental disorders. As a result of extensive research, the salmon and trout sectors are now able to optimise the use of marine-sourced Omega-3s, thus reducing their reliance on global supplies; but ultimately it is recognised that as aquaculture expands, alternative – probably plant-based – sources of this feed ingredient will need to be found. Similarly, fish meal has been an important component of some fish diets and, whilst some plant-based replacements have been found and are in use, the search continues for alternatives that have the appropriate amino acid profiles, digestibility and palatability.

Unlike terrestrial forms of farmed animal production, many of the species we now cultivate in aquaculture are little changed from their wild counterparts. Selective breeding programmes are becoming ever more sophisticated and our ability to target desirable production traits is also advancing rapidly. A combination of better disease treatments and alternative feeds, coupled to selectively-bred stock with improved disease resistance and the capacity to use feed materials more efficiently and from a wider variety of sources, will help to ensure that aquaculture continues to be sustainable.

In Southeast Asia, polyculture, or integrated multi-trophic aquaculture, has been practised for thousands of years. A typical example might be to feed household waste to chickens, for the chickens droppings to be used to fertilise freshwater ponds to stimulate the growth of phytopkankton as the basis of a food chain designed to feed fish, which will eventually be harvested as a source of food and income. However, "Western" aquaculture – a more recent development – has evolved as a series of monocultures, with production focused on single species. A considerable body of research over the last 15 years has explored the potential to integrate shellfish and seaweed production with finfish production to create a "virtuous" and potentially profitable circle, with the shellfish and seaweeds assimilating the particulate and soluble waste from the fish farms to produce additional marketable products, whilst reducing the environmental impact of the fish farm. Whilst in principle this scenario has merit, so far it has not provided sufficient economic or environmental benefits to attract widespread acceptance by the industry. However, as the industry continues to expand, and pressure to use our marine "space" more efficiently increases, co-location of aquaculture developments, and hence multi-trophic scenarios, may well start to appear.

There is no doubt that aquaculture will continue to expand globally – there is little alternative if we are to feed the rapidly-growing population and one whose per capita consumption of food derived from both marine and freshwater sources is increasing. The UK, and Scotland in particular, is well placed to contribute to that development. Although we cultivate relatively few species, we should not perhaps be concerned. Other forms of terrestrial agriculture have flourished by developing different varieties of a few domesticated species. We do not farm different species of chicken, pigs or cattle – we have simply selected desirable traits and created the huge variety of farmed animals we now accept. The speed with which aquaculture has expanded has resulted in some environmental issues, which will need to be continuously monitored and addressed. Disease, as with other forms of intensive terrestrial agriculture, remains a significant and ongoing challenge. A robust regulatory regime, together with existing research capacity and a positive policy landscape, suggests that aquaculture in Scotland will expand and be sustained in the longer term. Our capacity to support and influence the development of aquaculture globally through collaborative projects and providing world-class education and training will also ensure that we will continue to contribute to food security and support fragile rural economies.

> **"A robust regulatory regime, together with existing research capacity and a positive policy landscape, suggests that aquaculture in Scotland will expand and be sustained in the longer term."**

Which species?

Salmon

Salmon are the most successful and most popular fish farmed in Scotland, enjoying an almost iconic national status on a par with Scotch whisky, but other fish are also farmed and various experiments have been conducted in the past to see if other species would be both practical and profitable. One venture to farm cod was not a success – because the economics didn't work. Whilst cod stocks were depleted and feared to be close to collapse, other white fish such as haddock were still being caught in large volumes, and although farmed cod was targeted as a high-value niche product, production costs were still too high to attract a sufficiently large enough customer base to support an industry.

There has been considerable investment in developing halibut and, whilst it is produced in small volumes, the difficulty and associated cost of producing consistent numbers of high quality juveniles continues to limit the potential of this sector to expand. The UK led the development of turbot as an aquaculture species, but more favourable climatic conditions for on-growing in France and Spain ultimately led to production moving out of the UK. Trout remains a mainstay in terms of land-based production, but volumes remain low and the large retail market is focused on salmon – although some sea trout and rainbow trout are produced in small volumes at sea. Other finfish species have been explored, ranging from sole, seabass, lumpsuckers, hake and haddock to more exotic species such as tilapia and barramundi produced in land-based recirculating water systems. All, for various reasons, have failed to take off commercially in the UK.

Shellfish

European lobsters have long been an interest for aquaculturists and fishermen. For many years, the UK Government invested heavily in this species, with a view to restoring and enhancing wild stocks. However, the economics of this process remain challenging and, whilst production of lobsters for restocking is carried out, the real commercial value of this process is highly questionable. With respect to aquaculture, interest remains, but production costs and risks remain high and this will continue to limit ambitions with this species. However, a recently-awarded multi-million Euro grant to assess the potential for culturing the European Crawfish in a land-based recirculated water facility in North Wales may hail a new frontier.

Scallops are cultivated to a limited extent and there is recognition that demand for this species could outstrip wild-caught supply. However, the time for stock to reach a marketable size continues to limit investment in large-scale cultivation. The blue mussel grown on ropes is now a familiar sight in many Scottish sea lochs and there is potential to expand production of this sector, given appropriate growing areas and export markets.

Pacific oysters remain popular and there is renewed interest in cultivating native oysters. Some companies have dabbled with other shellfish species, such as tropical prawns in recirculating systems, but again, the economics remain challenging.

Bivalve shellfish are highly efficient filter feeders and, as a result, they have the capacity to concentrate both food and a range of potential natural and human-derived contaminants.

Maintaining high water quality is fundamental to the long-term sustainability of this industry. Some types of phytoplankton (algae) are toxic, forming harmful algal blooms. Whilst these are a natural occurrence, they are regularly responsible for contaminating shellfish, preventing harvesting and sales until toxin levels are deemed safe by the Food Standards Agency (FSA). Bacterial and viral contamination of shellfish as a result of sewage overflow is also a periodic problem which impacts on public health and is, therefore, carefully monitored by the industry and the FSA. Thankfully, Scottish coastal waters are generally of a high standard which, coupled to ongoing monitoring by industry and regulators, ensures that products from Scottish shellfish farms conform to rigorous hygiene standards and contribute to an expanding area of aquaculture production.

There is no room for complacency, however. Parts of the mussel shellfish sector have been forced out of business in recent years because of the increased presence of *Mytilus trossulus* – a mussel species that although not recognised as non-native, in some conditions outcompetes *Mytilus edulis* – the blue mussel we are familiar with. This species of mussel is associated with a lower meat yield and has a particularly fragile shell, which makes the individuals less economically desirable, ultimately reducing the profitability of the sector. Further research is needed to understand the conditions which favour this economically-damaging species and what impact this species and its hybrids with *M. edulis* have on the sustainable growth of the Scottish shellfish industry.

Seaweed

In China, seaweed farms are so large that they can be seen from space. Most of this production is for human consumption. In the West, seaweed is very much a niche market and one generally served through the harvest of wild stocks. However, with increasing interest in the use of seaweed as a source of biomass for energy production and the potential to extract some useful and potentially valuable by-products, pilot-scale plots of seaweed production have been established.

The authors

Dr Nabeil Salama

Salama is an epidemiological modeller concerned with the transmission of pathogens or parasites, such as sea lice, in the aquatic environment, both from wild fish to farmed individuals, and between and within aquaculture facilities. He has been based at the Marine Laboratory in Aberdeen for five years and spent the early part of his career studying terrestrial diseases. He uses epidemiological and oceanographic models to investigate the spread of disease, in order to inform spatial methods of disease management.

Dr Matt Gubbins

Gubbins is the manager of the Marine Spatial Planning Programme at Marine Scotland Science, based at the Marine Laboratory in Aberdeen. An ecotoxicologist by training, Matt has acted as an advisor to the planning and regulatory processes for marine aquaculture in Scotland since 2001. His work in marine spatial planning involves using models to map the constraints on future fish farm locations and identifying optimal locations, so the industry can expand in a sustainable manner.

Dr Iveta Matejusova

Matejusova is a group leader of the Aquaculture and Environment Group at MSS, based in Aberdeen. She joined MSS in 2001 as a parasitic taxonomist and ecologist, later moving on to molecular genetics, focusing on the molecular characterisation of fish pathogens, host–pathogen interactions and molecular epidemiology. In her work, she uses her background and novel molecular technology to study the genetic basis of susceptibility and resistance of fish and shellfish hosts to a range of aquatic pathogens and the transmission of pathogens in aquatic environments, and develops diagnostic tools for the discrimination of pathogen strains and populations.

Dr Mark James

James is the Operations Director of MASTS, but for the last 20 years has worked at the interface between science, industry and policy in aquaculture. This has involved running a number of large collaborative programmes of aquaculture-related research.

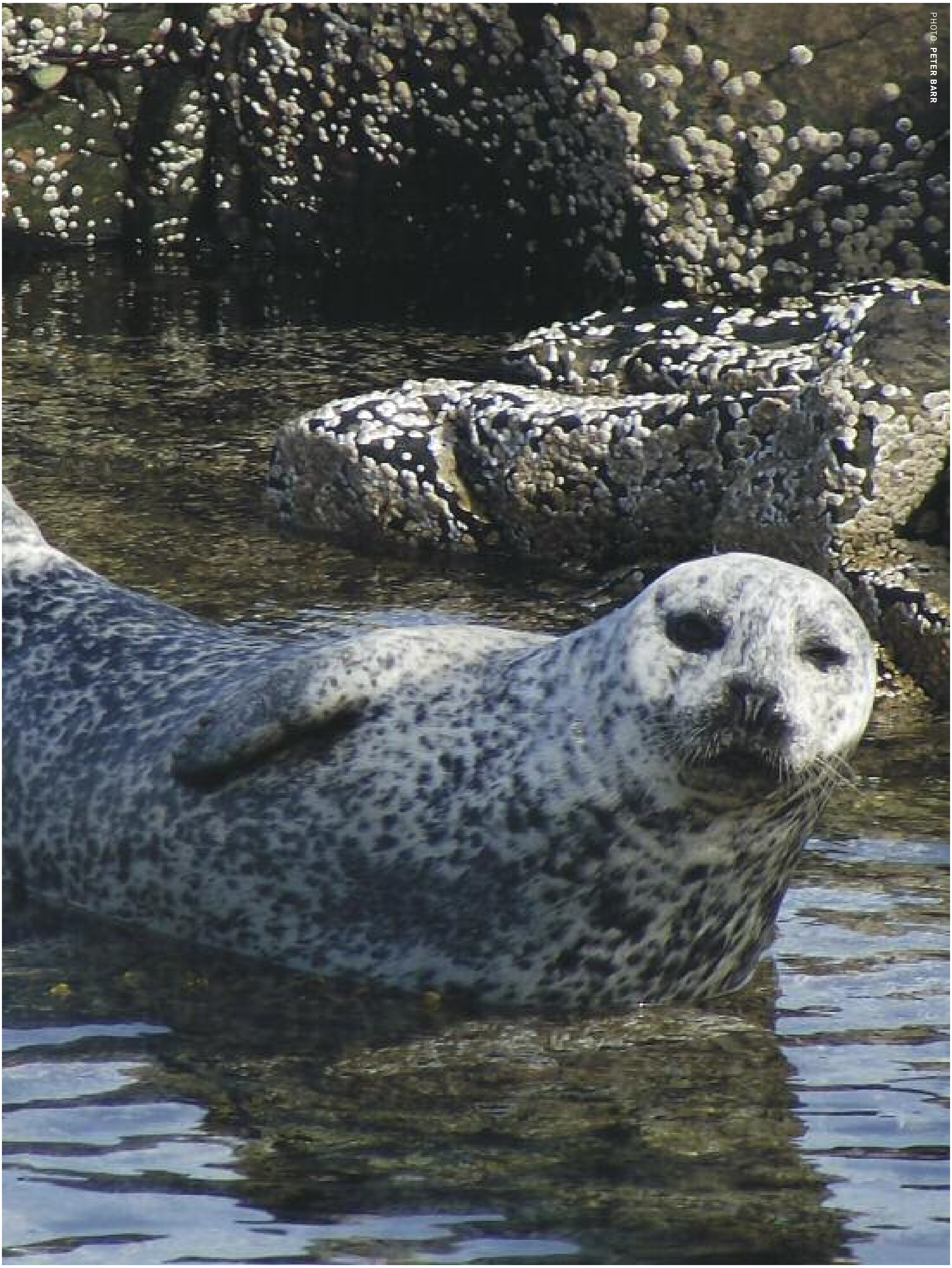


PHOTO: PETER BARR

Profile **The Marine Alliance for Science and Technology for Scotland (MASTS)**

Partnership in action

As science develops and the amount of information on a single subject increases, it becomes increasingly hard to be "an expert" in any one discipline. In addition, the problems that society now faces are complex and require expertise across many disciplinary boundaries to come up with solutions. An increasingly common approach is to form interdisciplinary partnerships and work closely together, a strategy that also provides opportunities for the sharing of resources, reduces competition and increases efficiency.

A wide range of experts is needed to study the marine ecosystem, including all types of biologists, plus physicists, climate experts, chemists and sedimentologists, and the interaction between different people, industries and the socio-economics of human behaviour is increasingly interwoven into the study.

The Marine Alliance for Science and Technology for Scotland (MASTS), which was established in 2009 with support from the Scottish Government, is an excellent example of scientific partnership in action. MASTS is a cooperative initiative that brings together the majority of Scotland's marine research capacity. It pools the talent of over 700 researchers and the management of resources consisting of over £66 million annually, in marine science from across Scotland. The primary focus of the MASTS research agenda is scientific excellence, but it also actively responds to the Scottish Government's Marine Vision for clean, healthy, safe and productive seas. MASTS will help to deliver this strategy through a better understanding of marine systems and their biological and physical dynamics, and has established three overarching Research Themes to promote these objectives, underpinned by research forums which are the major delivery mechanism for MASTS science.

MASTS Research Themes

Dynamics and properties of marine systems

This theme embraces the fundamental physical attributes and dynamics of marine systems including marine physics, chemistry, sedimentology, geomorphology and oceanography. It also includes technological developments that allow improved interpretation of marine systems.

Productive seas

This is a key area of MASTS activity, with major scientific challenges encompassing the balance of exploitation against the resilience and capacity of natural systems to supply resources against a backdrop of increasing demand and climate change. Both energy and food security are included and are fundamental drivers of marine science.

Marine biodiversity, function and services

The link between the diversity, distribution in space and time, and resilience of marine organisms is central to this theme. It also encompasses the role of marine biodiversity in supporting ecosystem function and providing ecosystem services across the variety of marine habitats, from coastal wetlands and estuaries to the deep sea, as well as research on the societal value that is placed on these systems and their ecology.

Members

The MASTS group is drawn from across Scotland and reflects the strength and depth of Scottish marine expertise, and has been growing as new partners join.

MASTS
Annual Science Meeting


The Marine Alliance for Science and Technology for Scotland will hold its fourth Annual Science Meeting (ASM) on Wednesday 3rd–Friday 5th September 2014 at the Heriot-Watt University Conference Centre, Edinburgh.

This cross-disciplinary meeting brings together members of the marine science community, with the aim of promoting and communicating research excellence and forging new scientific collaborations. The cross-disciplinary nature of the event, as well as the high calibre of the selected talks, means that scientists can broaden their knowledge in marine science as well as benefit from expertise and ideas gained in a range of fields other than their own.

Science presentations and e-poster sessions will take place on the first two days (Wednesday 3rd and Thursday 4th September), together with Plenary Speakers and opportunities to network. On the third day (Friday 5th), the venue will host a number of meetings and workshops.

Details regarding abstract submission and registration will be available in May 2014.

We also invite you to join us at the conference dinner and ceilidh (with the Hoochie Coochie Band) to be held on the evening of Wednesday 3rd September at Edinburgh Zoo.

Anyone interested in exhibiting at the 2014 event, or anyone wishing to showcase or demonstrate a piece of equipment or a technique should email Dr Emma Defew on masts@st-andrews.ac.uk

Visit: **http://www.masts.ac.uk/annual-science-meeting/**

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