Marine microorganisms form the foundation of healthy ocean ecosystems and successful marine industries

Abstract

Although less conspicuous than marine animals and plants, marine microorganisms comprise 50-90% of ocean biomass, are responsible for ~50% of global primary production, drive the ocean's major biogeochemical cycles (e.g., C, N, P, S, Fe) that ultimately control climate, and can include pathogens that cause disease in marine organisms and humans. Microorganisms provide the basis for all marine ecosystem services, which in Australian waters are valued at $42 billion per year. The diversity, distributional dynamics and functioning of marine microorganisms have direct relevance to the welfare and economy of Australians, by influencing aquaculture and fisheries yields, global climate, and marine ecosystem and human health. Maintaining marine microbial processes, on which life depends, is therefore critical to Australia's economic and social development.

Background

Marine microbes constitute the bulk of ocean biomass and perform the majority of oceanic photosynthesis, meaning that they directly control energy and material inputs into the marine food-web, which subsequently drives marine productivity and fishery yields (Azam et al. 1983). By performing the key chemical transformations within the ocean's major biogeochemical cycles (C, N, P, S), marine microbes also strongly mediate the ocean-atmosphere exchange of climatically important gases, which ultimately controls the global climate (Falkowski 2008). However, despite their fundamental importance in the global ocean, we currently lack a basic mechanistic understanding of microbial dynamics, particularly within Australian waters. Indeed, due to the vast diversity of microbes and their associated metabolic processes, we cannot yet accurately estimate the net effect of microbial activity in most parts of the ocean, nor predict their response to environmental change (Ducklow and Doney, 2013).

Microorganisms are the first responders to natural or man-made changes (including e.g. nutrient enrichment, waste discharge and oil spills) to the marine environment, acting as early warning indicators of changes in the health of ocean ecosystems, and their activities can either augment or buffer the negative influences of human and natural impacts (Atlas and Hazen 2011). The eminent ecologist Jeremy Jackson has argued that we are in the midst of a major and fundamental transition in marine ecosystems: "the rise of the microbes". That is, as a consequence of human induced stressors, such as diminished water quality, increased atmospheric gases and overfishing, we are entering an era where the impact of microorganisms on coastal civilisation will be unprecedented.

While most marine microorganisms are harmless and even beneficial, uncontrolled proliferation of certain taxa can result in disease outbreaks or harmful algal blooms (HAB). Research into marine diseases is now an emerging global priority as a result of outbreaks that have altered marine ecosystem structure and stability and had human health implications (Plowright et al 2008; Harvell et al 2002). HAB's caused by a variety of microorganisms are also increasing in distribution, frequency and severity worldwide with more frequent incidents of human poisoning, fish mortality and adverse effects on other water supplies (Paerl and Otten 2013).

In addition to the negative effects of marine microbial pathogens, the relationships between microorganisms and marine fauna and flora can often also be mutually beneficial. As with the human microbiome, marine microbes form symbiotic relationships with a range of marine animals and plants that provide ecological functions including enhancement of nutrition, enhancement of thermal tolerance, assistance with reproduction, waste reduction and the production of chemicals used in defence and immuno-competence (McFall-Ngai et al 2013). Positive symbiotic interactions between marine macro- and microorganisms form the basis of a sustainable, resilient and healthy ocean ecosystem (McFall-Ngai 2002).

We have entered an exciting time for the field of marine microbiology. Important discoveries that challenge our understanding of fundamental marine processes are happening regularly due to advances in ‘omics technologies, cell imaging and computational capacity, improvements in sampling scale and resolution and evolution of bioinformatic and theoretical approaches. Combined, these multidisciplinary methods are facilitating the quantitative connection of microbial metabolism to marine biogeochemical cycles. The next steps will be forged from long-term, integrated *in situ* datasets, microscale experimentation, and the emerging integration of environmental microbiology with concepts of modern ecology and ecosystem models. Predictive modelling tools, that incorporate microbiological processes, will be crucial for conservation management, assessing impacts from global climate change, marine biotechnology and all the industries that rely on a healthy ocean environment.

Australia has a proud history of research in marine science, in particular within focus areas such as coral reef and intertidal ecology, marine mammals and fisheries. However, recent technological developments and scientific leadership now places Australia in a unique and timely position to expand its marine research focus to the microscopic ocean inhabitants that are the primary biological determinants of ocean health. Australia’s continued status as a world leader in marine economics, conservation and management rests on our ability to understand and predict the response and resilience of these communities. Out-of-sight can no longer be considered out-of-mind.

a. Brief overview of the field of marine microbiology in Australia

Who does this work in Australia (institutions, # research scientists involved):

At least 15 Australian institutions currently have strong marine microbiology research activities, contributing to approximately 5% of the global publications on marine microbial biodiversity and microbial processes (Web of Science). These organisations comprise research agencies (CSIRO, AIMS, SARDI), and universities Notably, the number of active researchers is increasing rapidly as the field expands.

Marine microbiology is a rapidly emerging field that is intrinsically linked to biotechnological advances in sequencing, computation, bioinformatics, imaging and sampling. While biogeochemical measurements have been made for > 50 years (O_2 production, C fixation) the modern field is <30 years old, but is evolving at an unprecedented pace. However, despite being an island continent with fundamental economic, cultural and meteorological dependence upon oceanic processes, Australian microbial ecology has lagged behind other nations. We currently know very little about the composition or biogeochemical potential of the microorganisms inhabiting Australian waters. During a period when there is strong evidence that changing climate patterns are altering the functional dynamics of Australian marine ecosystems (Ridgway & Hill 2007) there is an urgent need to comprehensively examine the microbes, which form the core of ocean function, within Australian waters.

Australian marine microbiologists are among the best in the world and have contributed to the “*At or Above World Standard*” ERA rankings in microbiology achieved by several of the research institutions where marine microbiology is a research focus. The Australian marine microbiology community is involved in a number of high profile global research programs including the Earth Microbiome Project (Gilbert et al. 2010), Genomic Observatories and Ocean Sampling Day. Marine microbiological research in Australia is funded by a large range of sources including the Australian Research Council, the Fisheries Research and Development Corporation and a number of philanthropic organisations including the Human Frontiers of Research, Gordon & Betty Moore Foundation, the Great Barrier Reef Foundation and Mitsubishi CSR. International funding for microbial research has also been obtained from the Joint Genome Institute, J. Craig. Venter Institute, Symbiomics (Marie Curie Initial Training Networks), while Australian research agencies (CSIRO, AIMS), Commonwealth Government Departments (ABRS, Bioplatforms), State Government Departments (e.g. NSW DPI; QLD DSITIA) and management agencies

(GBRMPA) consistently fund or support this area of research. Marine microbiology in Australia also leverages recent significant national investments into marine science infrastructure, including construction of the $120 million RV Investigator and $25.6 million funding of the Integrated Marine Observing System through 2015 and the $30 million funding for the National Sea Simulator at AIMS.

b. Relevance of the Field

Who are the end users who benefit/will benefit from this research (directly or indirectly):

Microbial research is relevant to food security, energy security, public health, and biodiversity conservation.

Commonwealth and State Environment departments and associated regulators are directly and indirectly the largest end user of marine microbiological research outcomes. However, research outcomes also directly feed into other key marine industries including tourism, fisheries and oil and gas. For example, fisheries and aquaculture industries are directly impacted by marine pathogens. In Australia the annual economic impact of harmful algal blooms (HABs) is estimated at $180 to $240 million, with immense losses from single bloom events. As examples, an algal bloom-induced tuna aquaculture mortality in Port Lincoln (1996) caused a $45 million loss, and a toxic dinoflagellate bloom in Tasmania (2012) contaminated bivalves, abalone and rock lobster, resulting in a $24 million loss, a temporary global recall of all Australian shellfish and an associated loss of reputation for all Australian seafood.

Infectious pathogens and parasites have also limited productivity in both established and emergent aquaculture industries throughout Australia. For instance, QX disease and Winter Mortality Syndrome (both the result of infectious parasites) have decreased the productivity of the Sydney rock oyster industry in Australia by up to 50% since the 1970s (Green et al 2011). A newly introduced viral disease (Pacific Oyster Mortality Syndrome) now threatens Pacific oyster farming in Australia (Lewis et al 2012). *Vibriosis*, caused by the ingestion of seafood (particularly oysters and crustaceans) contaminated with pathogenic bacteria (*Vibrio* spp.), represents a further health risk to consumers and an economic loss to impacted aquaculture industries (Murray and Peeler 2005). Marine microbiological research can also enhance the productivity of aquaculture. For example, the strategic location of oyster leases in regions of high phytoplankton production increases the yields from aquaculture leases and the culture of selected marine microorganisms as a food supplement, such as β-carotene from *Dunaliella* phytoplankton is a growth economy worldwide.

The economic value of the Great Barrier Reef (GBR) is estimated at $ 6 billion annually, through its support of associated tourism and fishing industries, but this precious resource is threatened by declining health due to many pressures including increasing disease outbreaks, which are responsible for a significant fraction of coral mortality. Not only is the functioning of the GBR dependent on the symbiosis between photosynthetic microbes and invertebrate hosts, microbiological research into the dynamics and etiology of coral diseases has begun to reveal links between environmental perturbations and the susceptibility of corals to disease and the virulence of coral pathogens, which may aid in future efforts to manage and prevent coral disease outbreaks (Bourne et al 2009). Similar microbial diseases are beginning to emerge in temperate waters, where massive die-backs of seaweeds and seagrasses are observed (Campbell et al 2011). This will not only impact the recreational value of the temperate coastline, but have economic impacts by influencing fisheries and other marine industries.

The Australian tourism market is tightly linked to the appeal of our beaches. Recently, severe blooms of toxic dinoflagellates and cyanobacteria have impacted thousands of kilometres of coastline and estuaries. The increasing occurrence of such outbreaks will have a damaging effect on our reputation for pristine ocean environments with high human amenity. Marine microbiological research is helping preserve public health by understanding, predicting and preventing the influence of microbial pathogens on swimmers, fishers and consumers of seafood.

Marine microbiology is also directly relevant to ports, oil and gas and mining industries. Through the WAMSI research network the effect of dredging on sponge communities and their microbial partners is being measured and used to inform management decisions regarding impact statements and the permitting of dredging activities for large scale oil and gas projects. Recently, work focused on the impact of dredging on increasing coral disease prevalence has had a direct influence on public sentiment and governmental policy surrounding dredging in the GBR marine park and specifically the Abbot Point expansion.

There is enormous scope to develop indicators of ecosystem health and disturbance using marine microbiological approaches. Microbes represent a potentially critical tool and solution for bioremediation of impacted environments. For instance, microbes are sensitive indicators of heavy metal stress in ecosystems suffering from anthropogenic contamination (Sun et al 2012). Similarly, research stemming from the Deep Horizon (Gulf of Mexico, 2010) and the Exxon Valdez (Prince William Sound, 1989) oil spill disasters, has found that native microbes in the marine environment are capable of completely mineralising oil and played a vital role in the remediation of these sites (Atlas and Hazen, 2011). This knowledge provides a baseline for future research into natural bioremediation processes with beneficiaries likely to include oil companies that maintain drilling or transport operations in the marine environment and the coastal industries such as fisheries and tourism that are potentially impacted by oil spills.

c. Science needs (key science gaps/needs/challenges)

- **Long-term and high spatial resolution base-line data on microbial diversity and function:**
  Long-term microbial time series studies are extremely challenging to achieve logistically but absolutely crucial scientifically, and have been instrumental in uncovering many of the fundamental dynamics controlling marine microbial populations in other regions (e.g., Karl et al 1995, Fuhrman et al 2006, Gilbert et al 2010). The lack of datasets describing long-term microbial community dynamics and rates of biogeochemical transformations is a critical national gap that hinders our ability to predict potential climate impacts (Webster and Bourne 2012). Observing microbial community diversity is now tractable with the declining expense of sequencing and should be a core measurement alongside other parameters.

- **Incorporation of microbial processes into ecosystem models**:
  Microorganisms are the foundation of marine food webs and ocean biogeochemical cycles, but are typically neglected, or considered as a single black box, within marine ecosystem and oceanographic models. The ecology and dynamics of microbial communities is complex. The challenge will be to integrate data collection, modeling and experimentation in order to distill the important factors that accurately reflect the rates and fluxes of compounds required for large scale models. This will require experimentation and modeling over a number of scales, from cellular-level models of metabolism of key functional groups to ecological distribution models of species. Furthermore, very little is known about how carbon and energy flows from the microbial fraction to higher trophic levels in an ecosystem. A more complete understanding of marine microbial function will allow for better integration of microbial processes into predictive models, which is critical for determining how environmental changes will alter the structure and function of the base of the marine food web.

- **Capacity to predict and respond to the public health threat of introduced, invasive and pathogenic marine microbes:**
  Natural populations of pathogenic marine microbes can have substantial human health implications and

associated economic costs. Evidence from other regions indicates that the geographic range of many marine pathogens is expanding as a consequence of climate change (Patz et al 2003). Understanding where, when and why outbreaks (blooms) of potentially harmful or pathogenic marine microbes occur will help to safeguard the health of the Australian public. Ultimately this knowledge will be important for the development of novel biotechnological solutions for the early detection, real-time monitoring, and mitigation of marine pathogens and HABs.

- **Predicting and preventing diseases of marine species:**
  Microbial disease is being increasingly recognized as an important structuring factor for communities of keystone, sessile habitat-formers, such as kelps and corals, as well as mobile species, like fish. While all higher marine organisms have permanent and mutualistic association with microorganisms, these interactions can become unbalanced through environmental stress or other ecological factors, ultimately leading to disease and death. A major challenge is to understand the principles and dynamics of the complex interaction network between microorganisms and higher organisms in order to identify early indicators and predictors of stress and disease. Key priorities for this area of research include:

  1) Developing an understanding of the physiological ecology of pathogen outbreaks, including the biotic (microbial community, life cycle) and abiotic (nutrient availability, physical oceanography) factors involved.

  2) Identifying mitigation strategies and treatments for disease outbreaks.

  3) Increasing public and scientific awareness of emerging marine pathogens and toxins.

  Fulfillment of these priorities will aid the development of novel biotechnological solutions for the early detection, real-time monitoring, and mitigation of marine pathogens.

- **Understanding the functional role of marine microbes in climate and climate change:**
  Photosynthetic microbes in the ocean ‘fix’ ~60 Gigatonnes of CO_2 into living biomass per year and in doing so drive the oceanic drawdown of CO_2 from the atmosphere, contributing to the sequestration of carbon to the deep ocean or sea floor via the ‘biological pump’. However, the absolute quantity of carbon that is ultimately sequestered into the ocean interior is largely determined by the amount that is metabolized and respired back as CO_2 by heterotrophic microbial consumers on its downward journey. Similarly microbes influence carbon drawdown capacity in coastal and urban ecosystems because they metabolise carbon in water and sediments, potentially leading to net release of CO_2 and other potent greenhouse gases such as methane (CH_4). Variability in marine microbial assemblages can drive shifts in the dominance of net autotrophy (photosynthesis) vs heterotrophy (respiration), which subsequently creates regional heterogeneity in the CO_2 budgets of the ocean. Furthermore, climate change induced changes in the activity and net importance of autotrophic vs heterotrophic components of the marine microbial foodweb may have substantial positive or negative feedback effects on climate change processes. However, in Australian waters we have a limited understanding of which regions are net autotrophic vs net heterotrophic and an incomplete understanding of how this balance changes during environmental change, greatly hampering our ability to predict carbon flux dynamics in our region and balance the national C accounting estimate. In addition to the controls on oceanic carbon flux, marine microbes also produce and recycle other climatically important gases, including methane, nitrous oxide and dimethyl sulfide (DMS). Interactions between marine phytoplankton and bacterial populations influence the amount of DMS that is released to the atmosphere, which has direct climatic relevance because DMS is a precursor for substances that act as cloud condensation nuclei in the atmosphere. However, while marine microorganisms are the key determinant of ocean to atmosphere DMS release, our understanding of the ecological processes that control the amounts and rates of DMS production is rudimentary.

- **Role of microbes in bioremediation, e.g. oil spills:**

Due to their diverse metabolic potential, microorganisms are the most efficient and economically sound method for bioremediation of contaminated and polluted sites, and following catastrophic events such as oil spills. An enhanced understanding of the microbial processes involved in marine bioremediation and resilience to human-based modifications to the marine environment will directly lead to improved tools and applications for environmental cleanup.

- **Public engagement:**
  There is a critical requirement for societal education regarding the importance of microorganisms for a healthy environment. Whilst the public are becoming more aware of the benefit of microbes for human health (e.g. probiotics, a healthy gut microbiota) we need to raise awareness that beneficial microbes are also key to Earth's habitability.

Key outcomes/ national benefit that would flow from investment in this area
By 2020:

- Improved sustainability (resistance, resilience) of natural marine ecosystems from a detailed understanding of the function of marine microbes (food webs, pathogens, symbionts).
- The development of rapid diagnostics for marine disease that will facilitate management responses aimed at safeguarding critical environments, including the GBR
- Detection and response to threats of marine pathogens and HAB's on public health
- Developing new diagnostic approaches for assessing seafood safety (i.e. detection of microbial pathogens and their toxins in seafood)
- Inclusion of new, more specific microbial bioindicator data into environmental impact statements and water quality guidelines leading to improved ecosystem management
- Improvement of the efficiency of aquaculture and fisheries by using microbiological data to predict regions of enhanced productivity
- The discovery of new natural products derived from marine microbes, including biofuels
- Integration of microbial knowledge and data into existing models of marine processes leading to improved prediction of ecosystem responses, in particular with respect to climate change and other anthropogenic stressors.
- World-leading continental scale framework for sustained ecological observing based on linkages with existing infrastructure such as IMOS.

by 2025:

- The development of efficient approaches to extract biofuels from marine phytoplankton
- The development of new biomaterials and pharmaceuticals derived from the products of marine microbes
- Use refined cell and ecosystem modeling to develop a more detailed understanding of the flux of energy and organic matter from the base of the food web to higher levels, to guide management and planning for marine industries, including fisheries
- The use of specific microbial bioindicators to detect oil spills and undiscovered oil reservoirs
- Use of microbes in the bioremediation of impacted marine environments
- The implementation of biotechnological solutions for the early detection, real-time monitoring, and mitigation of marine pathogens and HABs.
- Enhancement of microbial culture collections (deposit banks) for maintenance and exploitation of economically (pharmaceuticals, fuels) and ecologically critical microbes.
- Implementation of autonomous sensor arrays targeted to key microbial processes indicative of ocean health (e.g. toxicity, productivity)
- The capacity to prevent the commercially significant problem of marine biofilm formation from a better understanding of the underpinning microbiological processes

by 2035:

- Sequestration of climate active gases using marine microbes
- Next generation of microbial bioproducts for commercial and domestic energy applications
- Assisted evolution / adaptation of key marine species via active manipulation of their core microbial communities
- Novel pharmaceuticals and biomaterials of benefit to human health

Perspectives

Specific science priorities for the next 5 - 20 years.

During the last two decades the field of marine microbiology has matured to unravel the enormous diversity of marine microbial communities and elucidate their functional roles. This era of discovery provides a platform to fully integrating microbial processes into our understanding of ocean health and function. Within this context, some of the specific science priorities during the next 1-2 decades include:

A full integration of microbial processes into physical and chemical oceanographic processes: Largely as a consequence of technological constraints, microbial oceanography historically lagged physical and chemical oceanography, with simple questions such as; who are the key groups of microbes in the ocean and what are they doing, left unanswered. During the last two decades the field of marine microbiology has evolved dramatically. As early adopters of technological advances in DNA sequencing and bioinformatics, the discipline has revealed the identities and potential functions of marine microbial assemblages that were previously treated as a black box in marine ecosystem function models. However, we are yet to reach the point where we can accurately predict where and when specific microbial groups or functions will occur, which greatly limits our ability to fully forecast or model marine ecosystem function. Over the coming years, the integration of large multi-disciplinary data-sets with high spatial and temporal extent and resolution will provide the capacity to mechanistically predict how regional, seasonal and annual heterogeneity in ocean chemistry and physics will influence the diversity and functional capacity of marine microbial assemblages. For instance, we can begin to understand and predict how important regional oceanographic features, such as the shifting influence of the East Australian Current or the variable dynamics of the mesoscale eddy system in the Tasman Sea, will impact the functional responses of microbes. Importantly, such data-streams will allow the paramaterisation of ecosystem models with microbial information, reducing much of the current uncertainty in predictive ocean process models. This capacity to link microbial community functionality to physicochemical features of the environment will deliver a range of benefits including a greater capacity to predict patterns in the basal determinants of marine productivity and fisheries yields within Australian waters.

Understanding how the effects of environmental degradation and change will be buffered or augmented by the responses of marine microbes: A universal issue facing marine ecosystems is the continuing influence of environmental degradation and climate change. Determining if and how changing ocean conditions will alter microbial community structure and function, while identifying any positive or negative feed-back effects, is a fundamentally important challenge for marine science in Australia. Microbes are the first responders to environmental perturbation and also have the capacity to buffer or mitigate ecosystem changes. For instance, accidental oil spills represent a major environmental threat to marine ecosystems, but marine microbes may act as important natural bioremediators – many have the capacity to rapidly and efficiently metabolize oil products from the environment. On the other hand, marine microbial processes may also exacerbate ecosystem shifts if a tipping point is reached – e.g. blooms of microbes in response to inputs of nutrient rich pollutants can lead to the formation of anoxic conditions and detrimental effects felt throughout the marine foodweb. Identifying functional redundancy within natural populations and thresholds and tipping points for declining microbial function is essential for enabling rapid responses and early management intervention to human activities in urban, coastal and oceanic environments. At present, the types and extents of microbial responses to natural and anthropogenic changes is largely unknown, despite the fact that this will ultimately determine the fate of marine ecosystem health and the industries that depend on marine resources.

Linking processes occurring at the microbial-scale to the global ocean scale: The influence of microbial diversity and activity shapes the productivity and biogeochemical function of the ocean at a global scale. However, this global influence is the product of microbial processes occurring at much smaller, microbial-scales. Many important marine chemical transformation processes occur with specific microenvironments or as a consequence of microbial interactions that occur within cell-to-cell scenarios that occupy only a fraction of a drop of seawater. Traditionally, oceanographers have 'averaged out' many of these important microbial-scale processes by taking large-volume water samples. As a consequence, there is currently a vast disconnect between understanding the ecological processes that underpin ocean chemical cycling and the large-scale implications of these processes. Before we can fully understand how microbial activities influence the function of the ocean, strategies that allow accurate scaling-up of specific microbial-scale processes to ocean basin-scale patterns are required.

Deciphering the identities and impacts of marine pathogens and assessing their shifting influence in a changing ocean. Disease causing microorganisms (pathogens) can have a substantial impact on the stability of natural ecosystems, marine industries (e.g. aquaculture, fisheries) and human health. A number of species of marine bacteria, viruses and fungi are responsible for diseases in a variety of marine organisms and there is evidence that these diseases can have ecosystem level consequences by causing mortality among habitat-defining organisms including corals and seaweeds as well as iconic species such as turtles. Despite the increasing incidence of disease in marine systems, we still know very little about the causative agents or environmental drivers of disease outbreaks. Notably, there is growing evidence that the effects of climate change are enhancing the influence of marine pathogens by increasing their geographical range, increasing their virulence and elevating the susceptibility of their animal and plant hosts (Plowright et al., 2008; Harvell et al 2002). A greater understanding of the dynamics of marine diseases and the ecology of microbial pathogens will help safeguard ecosystem and public health. Indeed in many cases, these research efforts may have tangible environmental management and public health benefits. For example, instead of identifying the outcome of a disease outbreak in a marine pathogen or HAB, which may be too late for remedial or mitigation management, identifying relevant shifts in environmental conditions or microbial communities would enable earlier intervention.

> **Exploiting marine microbes to solve energy demands and develop high-value products.** Marine microbes provide a huge natural reservoir of organisms with a diversity of lifestyles and metabolic/nutritional strategies that can be harnessed for a wide variety of applications including pharmaceuticals, nutraceuticals, biofuels, and enhanced animal feedstock (aquaculture and agriculture). For commercial application, this requires the discovery and exploration of "culturable" species that can be reliably produced in high biomass. Growth conditions could then be manipulated to favour production of useful compounds.

Why the above research needs to be performed within the context of the Australia marine environment: The Australian marine environment has several unique factors that limit our ability to extrapolate an understanding of microbial processes from work done in other oceanic provinces. Our ocean environment is unique in that both western and eastern coasts are influenced by southward flowing, warm, oligotrophic boundary currents. Furthermore, as an island nation, Australia is bounded byseven different oceans/seas (Indian Ocean, Timor Sea, Arafura Sea, Coral Sea, Tasman Sea, Pacific Ocean, Southern Ocean) and hosts a highly dynamic regional oceanography including mesoscale eddy fields. Australia is also home to the world heritage listed Great Barrier Reef and has responsibility for the effective management and conservation of this internationally significant icon. Additionally, the Australian marine environment has been identified as a climate change hot-spot, with seawater temperatures in the Tasman Sea rising at four times faster than the global average. Microbial responses to this environmental variability and long-term change are regionally specific and will have potentially important feedback effects, particularly in the Southern Ocean, where most anthropogenic CO_2 has been absorbed, warranting Australian-centric examinations of marine microbial ecology. However, as Australia provides unparalleled access to such diverse ocean regions, as well as their points of intersection where water bodies mix, research carried out in Australia will be of considerable value when extrapolated to global scales. Not only this, given that the East Australia Current is one of 5 western boundary currents (WBCs) in the global ocean, research carried out in Australia will garner international attention.

d. **Realisation**

Key infrastructure and capability requirements/impediments

To maintain and grow marine microbiology activities across Australia and maximize the economic potential and social benefits of this field, the following are required:

- **Development of *in situ* monitoring capabilities**

Microbes respond rapidly to environmental fluctuations. Remotely deployable, low-cost, autonomous, *in-situ* sampling and detection instruments will revolutionise our ability to monitor marine environments, enabling high-resolution measurements of microbial metabolic and regulatory responses to change at temporal and spatial scales relevant to microbial lifestyles. Such instruments would find wide applicability in diverse fields such as, early warning pathogen detection (fisheries), contamination detection (oil and gas), microbial oceanography, and environmental health evaluation.

- **In depth characterisation of important, microbially driven processes**

Observing which microbes are present in a community can provide insight into which processes are occurring. However, there is a disconnect between observing the biogeochemical potential of a community and the mechanistic understanding of how genomes are dynamically translated into living cells, communities and functional ecosystems. Transforming these observations into actual rates and fluxes requires in-depth characterisation of model systems. Focusing on a few model systems, e.g. microbes involved in primary production, sulfur cycling or important inter-kingdom symbioses, would allow us to scale from the cellular-level to ecosystem-wide models and crucially provide the opportunity to verify large scale models using bottom-up experimentation.

- **Availability of Research Vessels for Open Water Research**

Access to the Marine Environment extending beyond Australia’s coastline is currently extremely limited. While institute-specific research vessels, such as the Australian Institute of Marine Science’s *RV Cape Ferguson* and *RV Solander,* and SARDI’s *RV Ngerin* are occasionally used for marine microbial research, the wider scientific community only has limited access to these vessels. There is currently only one purpose-designed national oceanographic vessel (which currently only has six months operational capacity) to cover Australia’s entire marine environment. This is a substantial hindrance to efforts to understand the ecology and biogeochemical function of microbes in offshore waters and remote locations.

- **Accessibility Programs for ships of opportunity**

Traditional oceanography is restricted to large and expensive ocean going vessels where only a few samples may be taken at a time and only a fraction of the oceans surrounding Australia can be covered over the course of a decade. Long term monitoring of microbial communities and large scale modeling of global biogeochemical cycles requires the collection of high-density data over time and space. To fill this gap, an integrated system of various data-collecting methods needs to be developed. Everyday thousands of ships travel Australian's coastal waters. These include ferries, cargo ships, and private vessels such as yachts. To harness this existing network, these ships could be equipped with suitable instrumentation and transformed into ’citizen oceanographers’.

- **Commitment to long-term monitoring programs**

Currently there are no long-term (> 10 years) datasets available that describe baseline microbial processes or functions in the marine environment. Such long-term observatories are critically important to understand and model responses, outcomes and future trajectories; similar to what has been achieved for coral-reef research for decades. We therefore need to establish and continuously support a network of “microbial observatories” that monitor microbial processes in key marine habitats using a combination of autonomous in situ sensing augmented with more complex ex-situ analyses and experimentation.

- **Teaching and training**

Any future activity in the area of marine microbiology will require highly-trained and skilled researchers. Most Australian Universities do not have dedicated teaching programs in the field of marine microbiology and this should be addressed through the establishment of dedicated curricula. In addition, marine biologists and ecologists can be trained (upskilled) in microbial approaches and concepts and this can be done through dedicated workshops and other training activities. This will require the integration of multidisciplinary skills, spanning ecology, molecular biology, microbiology, mathematics, computer science and bioinformatics.

- **Computing infrastructure/Bioinformatic expertise**

Modern marine microbiology relies heavily on the knowledge garnered from large-scale nucleotide (DNA, RNA) and protein sequencing technologies. However, these approaches require substantial computational power and infrastructure for the analysis of very large data-sets, which is not always immediately available to researchers. The field of marine microbiology in Australia would benefit greatly from the wider availability of reliable and easy to access computational infrastructure. In addition, training of individuals with specific focus on marine microbiology and skills in analyzing large bioinformatics datasets is required.

- **Analytical capabilities**

Recent advances in the field of marine microbiology have been highly technology-driven. Essential research and analytical capability, such as DNA sequencing and microbial imaging and analysis infrastructure is available in Australia, but is currently geographically scattered (e.g. the only nanoscale Secondary Ion Mass Spectrometers (NanoSims) in Australia are located in Perth, while most of the DNA sequencing capacity is concentrated on the eastern seaboard). Greater access to analytical capacity will enhance the growth of marine microbiology in Australia.

- **Engagement with the community (citizen science opportunities)**

We need to engender widespread acknowledgement that marine microbes are primary determinants of a healthy ocean and as such microbial activities impact all end users of aquatic systems. This may be achieved through enhanced end user engagement, the promotion and utilization of citizen science opportunities (e.g. Ocean Sampling Day and the recruitment of “citizen oceanographers” to collect microbial data) and wider public outreach efforts in general.

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