ADVANCING MARINE SCIENCE IN SINGAPORE

The Marine Science Research & Development Programme (2015–21)

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A view of Lazarus and Kusu Islands against the city skyline of Singapore

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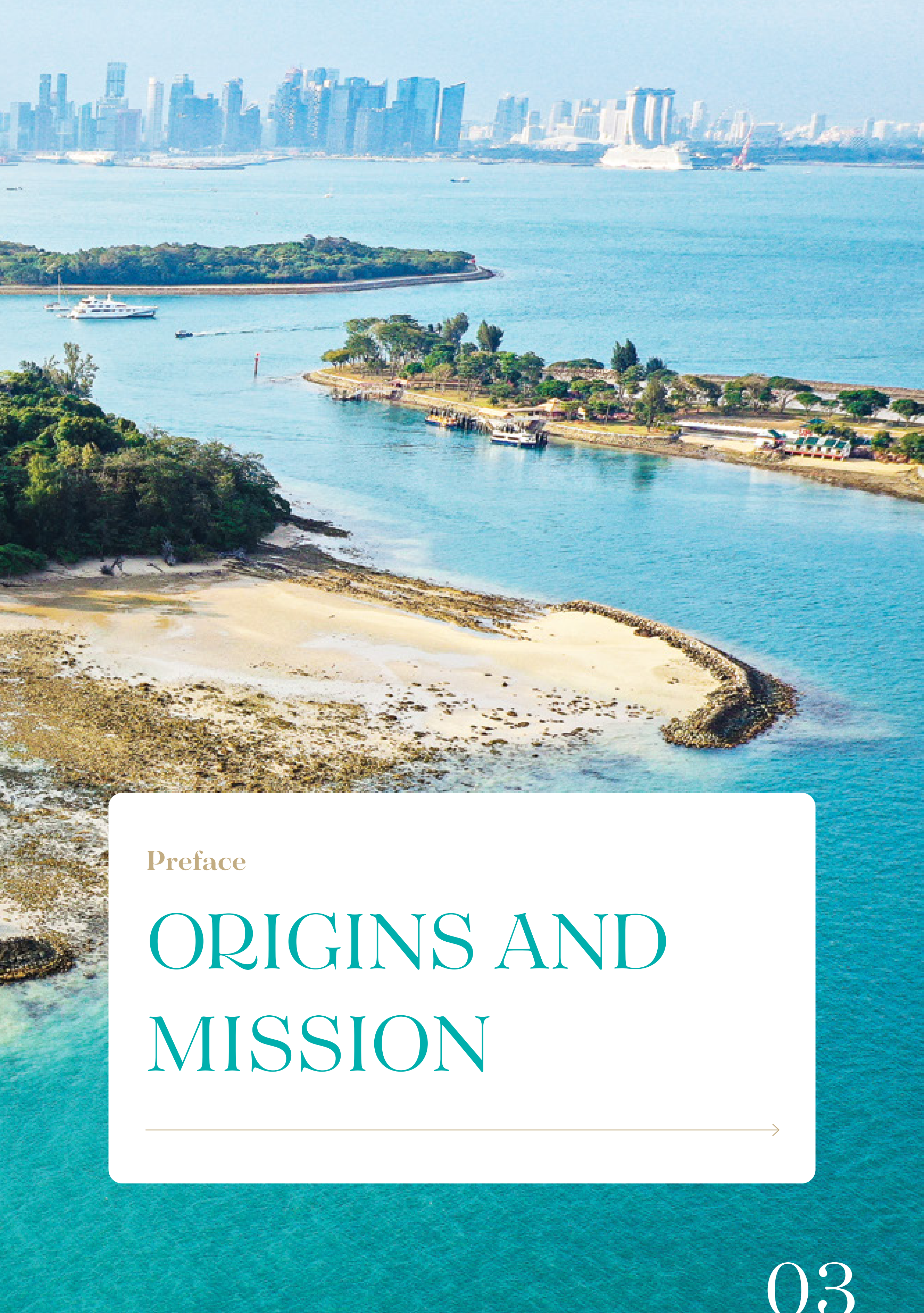
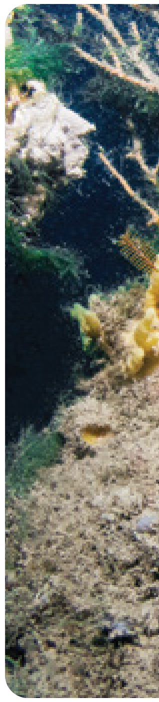


Preface

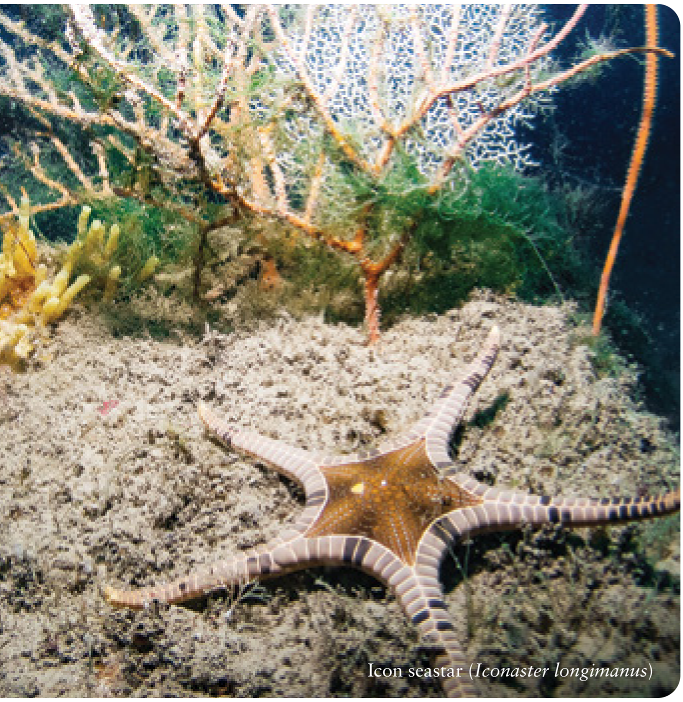
ORIGINS AND MISSION



Singapore is strategically located at the crossroads of the Pacific and Indian Oceans. Its unique position in Southeast Asia offers unprecedented opportunities for rapidly advancing research discovery in tropical marine science. As the world's busiest transhipment hub, Singapore is seamlessly connected to more than 600 ports in 120 countries. This connectivity presents immense challenges for biodiversity conservation, environmental health, urban development, and the mitigation of environmental stresses.

On the global stage, Singapore has a multitude of obligations for biodiversity conservation, environmental management and stress mitigation, minimising anthropogenic climate change impact, and natural resource utilisation (vis-à-vis agreements with the Convention on Biological Diversity (CBD), Intergovernmental Panel on Climate Change (IPCC), and International Seabed Authority (ISA), etc.). At the national level, Singapore has committed itself to a major sustainability and conservation drive to fulfil the environmental responsibilities of a first-world country in a region of rapid economic growth. It established the nation's first marine protected area at Sisters' Islands in 2016.

A national marine science research programme was therefore needed to secure and strengthen Singapore's position as a major maritime research player and support Singapore's sea-based economy in the long term. To this effect, the National Research Foundation (NRF) engaged Nanyang Technological University (NTU) with the National University of Singapore (NUS) to develop and lead a Marine Science Research and Development Programme (MSRDP) to address contemporary strategic needs for the numerous stakeholders in Singapore. Moreover, NRF allocated funds to renovate and reinvigorate the St. John's Island National Marine Laboratory (SJINML) as



Icon seastar (*Iconaster longimanus*)

a National Research Infrastructure facility for marine science activities in Singapore.

The MSRDP was conceptualised through many dialogue sessions and a workshop with NRF management, academics from institutes of higher learning (IHLs), government agencies, statutory boards, and industry players. This process identified many opportunities for Singapore to take a strong leadership in conducting high-impact research of societal and economic value (both at the national and international levels) relevant to tropical coastal cities around the world. Solutions for many environmental issues are needed and a holistic programme with strong foundations in fundamental research was thus urgently required. An International Evaluation Panel (IEP) of leading marine scientists was formed to oversee, advise, and review the programme as it evolved as a platform to fund innovative marine science projects, foster collaborations across institutions, and build capacity for addressing long-term environmental challenges.

I was honoured by the invitation to participate on the International Evaluation Panel to review research proposals submitted to the MSRDP. Reading and evaluating a large number of diverse proposals for the MSRDP was a big chore, but a pleasant one, because of the extremely high calibre of the proposed research. The activity also made me aware of the great depth and breadth of marine science at the St. John's Island National Marine Laboratory, the National University of Singapore, Nanyang Technological University, and the Singapore Centre for Environmental Life Sciences Engineering. Looking back from 2021, I think it is abundantly clear that the MSRDP has significantly enhanced Singapore's contributions to state-of-the-art tropical marine science and impacted global knowledge of life in the seas and the many anthropogenic assaults on it.

Michael G. Hadfield
Professor Emeritus
Pacific Biosciences Research Center
University of Hawai'i Manoa,
Department of Biology

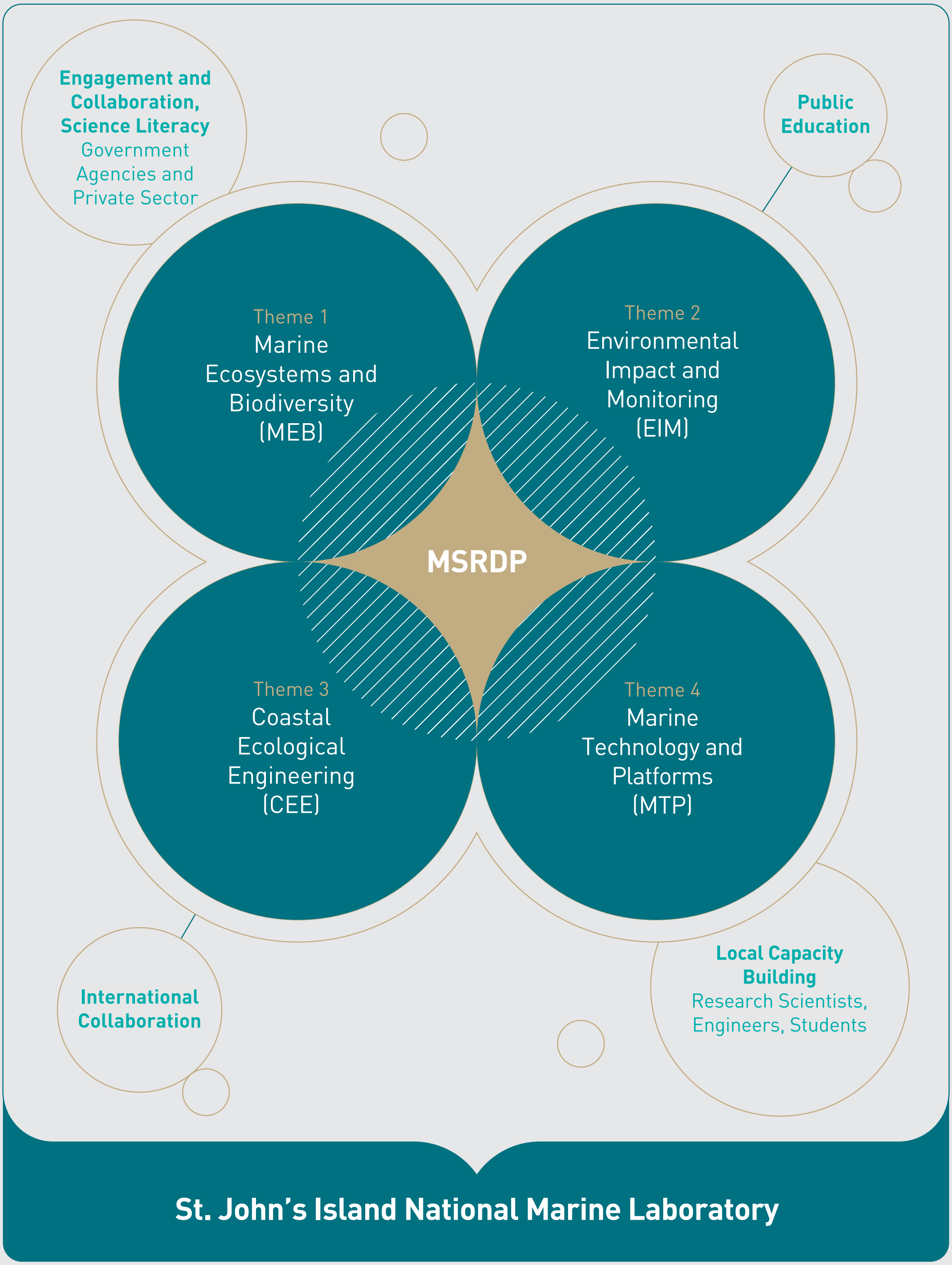
It is a great honour to have the opportunity to be invited to serve as a member of the MSRDP's International Evaluation Panel. It gave me an opportunity to learn from the creativity of all the proposals and the achievements from those research projects awarded. I have also admired and been impressed with the Singapore government's emphasis on and funding for marine scientific research, which could not be followed by other Southeast Asian countries. We saw outstanding results from the teams that received grants, after a rigorous evaluation and well-organised screening. Examples of research funded by the programme include: pollution prevention and control, marine life and ecology surveys, database establishment and ocean acidification issues, etc. The MSRDP's research contributes not only to Singapore but also to the sustainability of the world's oceans.

Kwang-Tsao Shao
Chair Professor, Institute of Marine Biology, National Taiwan Ocean University
Emeritus Research Fellow, Biodiversity Research Center, Academia Sinica


Pulau Hantu

The MSRDP's mission was to position Singapore as a global leader in tropical marine science research, and a driver and catalyst for strengthening a knowledge-based maritime economy. Over the six-year period, the MSRDP supported more than 30 research projects at the IHLs, many working with agencies, to increase our knowledge of regional waters and significantly advanced marine science in Singapore. The MSRDP was the first such programme by NRF to allow integration of the best ideas and talents across Singapore's research ecosystem, regardless of their institutional affiliations, and link them to operational agencies and organisations. Through academic workshops supported by the MSRDP, various international interactions and agreements were also established. The MSRDP also incorporated outreach elements, encouraging and supporting young students in marine sciences, and articulating and translating academic outcomes to national socio-economic needs. In addition, the MSRDP secretariat office became the *de facto* clearing house for marine science matters for NRF (including matters of the United Nations Convention on the Law of the Sea) over its six-year lifespan.

Throughout the programme, Singapore-based scientific expertise was upgraded, trained and co-ordinated under the '3 + 1' research domains of Marine Ecosystems and Biodiversity (MEB), Environmental Impact and Monitoring (EIM), and Coastal Ecological Engineering (CEE), supported by Marine Technology and Platforms (MTP). These domains were aimed at establishing Singapore as a leader in maritime and coastal development to: (1) improve quality of environmental monitoring and surveys to increase the baseline knowledge of the island's tropical marine environment; (2) better conserve or retain local marine habitats and/or minimise impacts of ongoing and anticipated reclamation works; and (3) generate scientific credibility and data to support the national agenda, and Singapore's regional and international commitments.


Engagement and Collaboration, Science Literacy
Government Agencies and Private Sector
Public Education
Theme 1
Marine Ecosystems and Biodiversity (MEB)
Theme 2
Environmental Impact and Monitoring (EIM)
MSRDP
Theme 3
Coastal Ecological Engineering (CEE)
Theme 4
Marine Technology and Platforms (MTP)
International Collaboration
Local Capacity Building
Research Scientists, Engineers, Students
St. John's Island National Marine Laboratory

The 3 + 1 research domains were as follows:

1 Marine Ecosystems and Biodiversity (MEB)

Singapore's unique position within the Coral Triangle coupled with its strong research infrastructure provide a competitive advantage as a major game changer in tropical marine science in Southeast Asia. Management of biodiversity in Southeast Asia is marked by a lack of consistent and large-scale data. For Singapore, the main threats to species arise from coastal modifications resulting in habitat loss, degradation, pollution, and impacts from invasive species. As a major transhipment hub, our marine environment is vulnerable to global introductions of pests and pathogens. The MEB programme was set up to strengthen the knowledge base that is needed as the foundation of legal and technical safeguards for the country's maritime and offshore businesses. MEB sets the stage for providing the needed dynamic baseline in which all subsequent challenges can be addressed.

Shrimp in an *Acropora* coral

2 Environmental Impact and Monitoring (EIM)

Environmental impact assessments (EIA) are now standard practice internationally. EIM served as a predictor and a tool for management purposes as well as for positioning Singapore to be a key player in urban environmental planning. The MSRDP provided a strong science-based national EIM programme with the best legal and management framework. EIM focused on the development of new, robust models for environmental assessment for tropical coastal seas. A series of projects allowed for improved monitoring of ecosystem health and stress factors and will be used to develop environmental models that predict long-term ecosystem impacts of shipping and associated activities.

3 Coastal Ecological Engineering (CEE)

Coastal cities contribute half of global GDP, and more than 65% of the world's megacities are on the coast. The urban coastal cities present significant challenges for the health and management of marine and estuarine environments, and it is necessary to design coastal structures in novel ways to reduce wastage, increase biodiversity, and raise Singapore's City Biodiversity Index (CBI). The focus of CEE was aimed at developing capabilities to mitigate impacts that result from urban development, rehabilitating and enhancing biodiversity in the coastal environment, and creating a vibrant healthy port environment. The MSRDP supports the development of engineered seawalls with optimal architectural, hydrodynamical, and biological properties for efficient ecosystem integration and resilience.

4 Marine Technology and Platforms (MTP)

MTP explored high-value novel materials, new processes, and systems development to add value to the above three domains, including integrated databases and other novel marine-based tools and technologies.


Pulau Jong

After six fruitful years, the MSRDP comes to an end in September 2021. As of now, one important research theme directly linked to the MSRDP, climate change impacts and the marine environment, will be further explored through a new NRF and National Parks Board programme. It is therefore a useful milestone to reflect on what has been achieved overall under the MSRDP and what may be required in the next phase of marine science research in Singapore. To address these objectives, the MSRDP team has documented the successes of the programme through this book, as well as organised the Marine Science in Singapore Conference (16 and 17 September 2021).

This book highlights the many educational, outreach, and international research collaborative efforts of the programme, and also features student interviews and collaborators' testimonials. In addition, the document provides an overview of the refurbished St. John's Island National Marine Laboratory and the Singapore Blue Plan, the latter a ground-up conservation-driven publication that describes the state of knowledge of the marine ecosystem in Singapore and the challenges ahead.

This MSRDP special publication is designed to complement the conference, which aims to provide participants with an understanding of current and future marine science research in Singapore. In addition, the conference will engage local agencies and solicit scientific inputs from selected renowned international marine science researchers. Related MSRDP domains, notably marine plastics pollution and aquaculture, will also be covered at the conference.

We gratefully acknowledge the excellent contributions by the MSRDP project investigators and the publication committee for curating and compiling the contents of this book. We also extend our thanks to the NRF for funding the programme, government agencies and industries for being engaged in several of the research projects, the IEP for its expert advice and guidance throughout the programme, and the marine science community in Singapore and beyond for the national and international collaborations.

Peter Ng
Director, MSRDP

Staffan Kjelleberg
Deputy Director, MSRDP

151 Conference presentations

17 International collaborations

Journal publications **163**

Projects with local agencies **6**

Public outreach events **116**

PhD students trained **35**

Polytechnic students mentored **51**

Explore students mentored **44**

Master's students trained **13**

Overseas placements for undergraduates **38**

This infographic reflects outputs of the MSRDP for Financial Year 2020 (FY2020)

Red feather stars (*Himerometra* sp.) extending their oral arms to feed

UNIFYING MARINE SCIENCE IN SINGAPORE

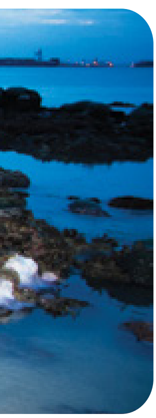
Contributed by Patrick Martin, Peter A Todd, Jani TI Tanzil

Through innovative projects and strategic initiatives over the past six years, the National Research Foundation's Marine Science Research and Development Programme has strengthened Singapore's marine science capabilities and addressed important gaps in the scientific understanding of our coastal and marine ecosystems. The MSRDP funded 33 research projects. Although these projects were grouped into four domains (Marine Ecosystems and Biodiversity; Environmental Impact and Monitoring; Coastal Ecological Engineering; and Marine Technology and Platforms), in many cases, different projects across the domains provided important complementary research. As a result, the MSRDP managed to advance basic knowledge regarding tropical seas and promote the application of that knowledge among agencies, industry, and policymakers.

A low tide at Kusu Island

The MSRDP has improved the coordination of marine science activities and is an excellent example of effective collaboration and co-investment between a number of scientific entities and industry. Such integrated research is delivering outcomes that will aid governments, industries, and the wider community, to make informed decisions for the benefit of the management of Singapore's marine estate and its rich biological resources. Most importantly, it will also motivate and encourage young people to pursue a career in the marine sciences.

Diana Jones
Executive Director, Collections and Research
Western Australian Museum



One of the MSRDP's most significant achievements is the increased collaboration among local and international academic institutions, industry, and government agencies. Through an 'all of Singapore' approach, the MSRDP broke down institutional and discipline-based silos by encouraging research groups and project teams to interact (especially across the four domains), share results, and work together, substantially promoting knowledge generation and translation through engagement with government and industry partners. The MSRDP also facilitated international collaborations via partnership-building workshops, overseas student exchange programmes, international conference attendance, and public outreach events. With the strong support of the two largest universities (which also provided additional scholarships), the MSRDP built up local capacity, developing a strong talent pool of Singapore-based scientists, engineers, and students—including graduate, undergraduate, polytechnic, and pre-university students. This is designed to set the stage for future research endeavours in marine science and strengthen the manpower needs of the marine sector.

The convergence and integration of research realised through the MSRDP have led to many new discoveries, partnerships, scientific papers, and follow-on projects. The MSRDP has also created a more unified marine science landscape in Singapore. This has facilitated strong links between fundamental and applied research, both for commercialisation and environmental management. The accomplishments of each project are summarised on the next page. Because many projects complemented others across the four MSRDP domains, they are not grouped according to the four domains, but are instead presented in an order that highlights the logical connections, especially between fundamental and applied research.

Anchor projects

The two MSRDP-funded anchor projects, MSRDP-P03: *Adaptation and resilience of coral reefs to environmental change in Singapore* and MSRDP-P05: *Ecologically engineering Singapore's seawalls to enhance biodiversity*, required substantial inter-institution and multidisciplinary research to address key knowledge gaps and find solutions for some of the more pernicious ecological and environmental challenges, such as those associated with marine urbanisation and coastal change.

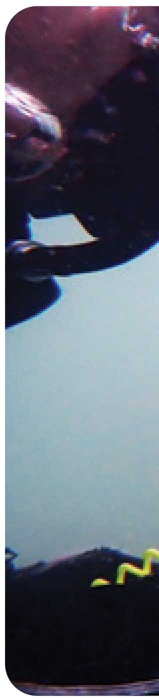
MSRDP-P03 has provided important insights into the adaptation and resilience of Singapore's coral reefs pertaining to environmental changes. These insights cover basic biology of the coral–algal symbiosis, how environmental conditions influence coral skeleton chemistry, the ecological factors controlling macroalgal growth and the health of Singapore's coral reefs, as well as the role of microbes for the coral holobiome and coral–macroalgae interactions. This project also led to a seed grant project (MSRDP-P38) that examined the genetic diversity and connectivity of coral communities. MSRDP-P05 has identified new ways to increase the biodiversity on Singapore's artificial coastal defences by creating and field-trialling 'biodiversity enhancement units' that provide shelter for intertidal organisms. This included testing the micro- and macro-biological responses to fabrication materials and the hydrodynamics of waves interacting with Singapore's seawalls. Directly attaching corals was also used as a technique to raise the ecological value of seawalls, and has resulted in a selection matrix for identifying the coral species most suited for transplanting to any particular setting. The two projects worked together extensively, yielding more than 10 collaborative papers, as well as many joint conference presentations and shared outreach events. Both projects have created strong links with international research institutions, including Scripps Institution of Oceanography, the University of Hong Kong, the Australian Institute of Marine Science, Curtin University, Swansea University, the University of Oxford, the University of Plymouth, and Silliman University, and shared their research through 110 papers and 70 conference presentations. Several new grants have also been captured based on the research accomplished under both anchor projects, including a Cities of Tomorrow grant, a Temasek Foundation grant, and two Australian Research Council-Singapore NRF grants.

Assessing and monitoring environmental impacts

Given the ever-increasing pressure on Singapore's marine habitats from local, regional, and global pressures, several projects across the four domains addressed a broad range of topics relating to environmental impacts. These projects have provided both fundamental insights into existing and emerging environmental threats, and translatable knowledge that can feed into adaptive resource management practices.

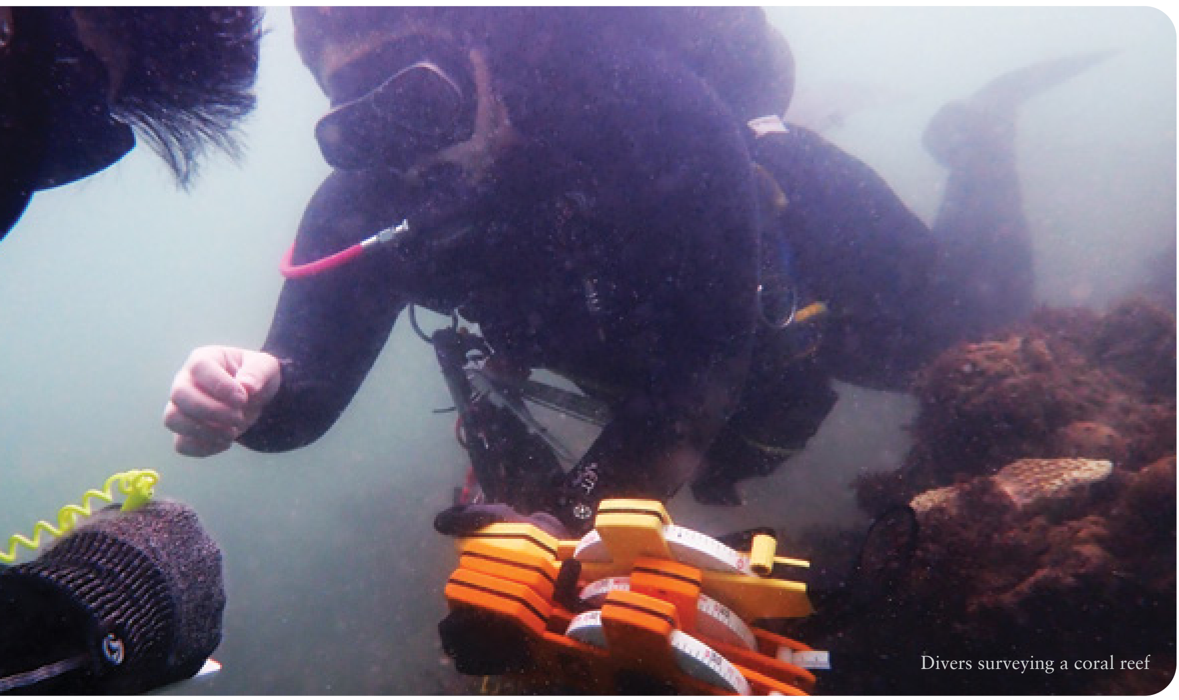
A critical concern in Singapore is the impact of suspended sediments, for example, from land reclamation and shipping traffic, which can harm sensitive ecosystems such as coral reefs. MSRDP-P04 established that mucus generated by corals and other reef-dwellers can bind sediment particles and make them more buoyant, so they remain suspended for longer, and are more readily resuspended once settled. Modelling simulations showed that different types of shipping traffic promote sediment resuspension to different degrees. This work highlights how organisms provide feedback on environmental conditions that is not typically considered in environmental impact assessments, and can guide development of more accurate environmental quality objectives for tropical coastal waters.

MSRDP-P33 and MSRDP-P45 investigated microbial communities in aquaculture-impacted sediments in the Johor Strait. MSRDP-P33 measured longer persistence of pathogenic microbes when in the presence of biologically derived,



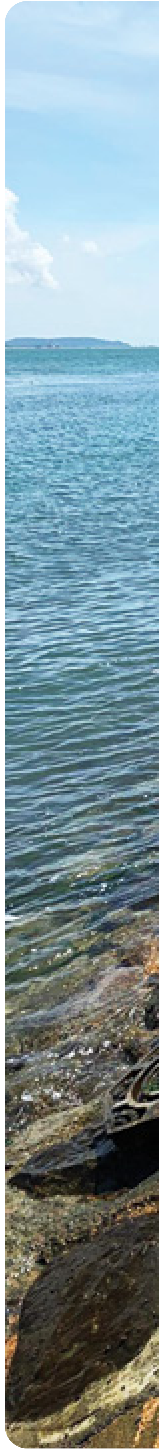
suspended particles (so-called marine snow), and also found long persistence in sediments at the seafloor. This means that resuspension of sediments may act as a source of pathogens to the environment. The team also developed the first optimised molecular method to detect viable cells of *Tenacibaculum maritimum*, a bacterium that infects fish and causes economic losses to aquaculture operations. MSRDP-P45 showed that sediment samples across both the west and east Johor Strait consistently contained microbes harbouring resistance genes against important antibiotics, albeit at very low abundances. These findings are invaluable for safeguarding Singapore's health and aquaculture industry. Both projects have resulted in strong, synergistic relationships with the Singapore Food Agency's Marine Aquaculture Centre, and led to a follow-on project through NRF's Competitive Research Programme.

As a major shipping hub, Singapore is particularly vulnerable to invasive species. MSRDP-P39 conducted a systematic assessment of the infestation of the mussel *Mytella strigata*, which has recently invaded Singapore. Large aggregations of *M. strigata* were found in Singapore's northern nature reserves. Few predatory snails were found on these aggregations, suggesting a lack of local natural predators. The project was carried out jointly with the National Parks Board, and made practical recommendations to mitigate the spread of this species. Although several mussels are invasive around the world, taxonomically identifying Southeast Asian mussels remains notoriously difficult, which greatly hampers efforts to track biological invasions. Project MSRDP-P25 clarified the phylogenetic relationships and taxonomy of various common mussel taxa across South and Southeast Asia using morphological and molecular methods. The team, which included scientists from Thailand and Indonesia, has made several taxonomic revisions, proposed a new genus, and established a robust suite of characters for species identifications. This fundamental knowledge is critical to accurately track the movement of invasive mussels in Singapore and across the region.



Divers surveying a coral reef

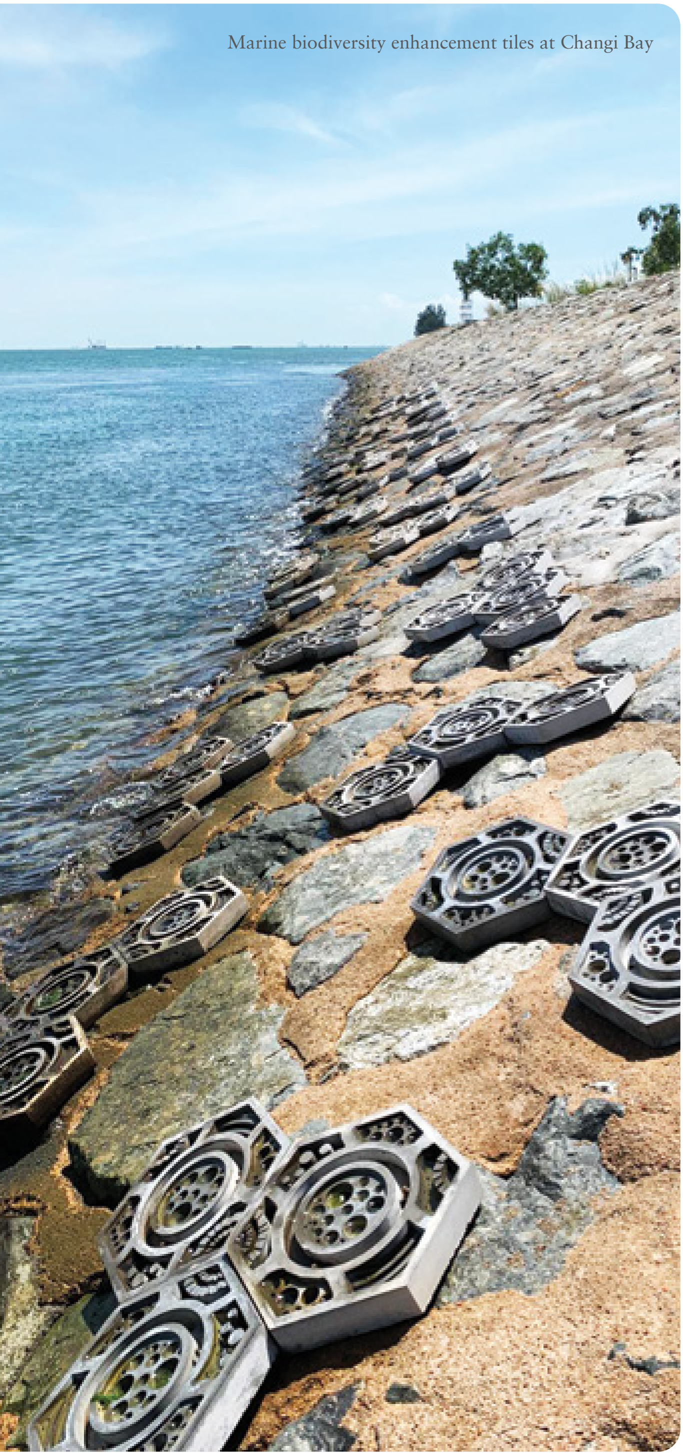
Seagrass flower (*Enhalus acroides*)



Ocean acidification is a serious emerging threat in a region harbouring high coral diversity, such as Singapore. MSRDP-P32 showed that seawater pH in the Singapore Strait is controlled by the seasonal delivery of dissolved organic matter from peatland-draining rivers. At sea, most of the organic matter decomposes to carbon dioxide and acidifies the water, yet some remains intact and absorbs sunlight. Ocean currents seasonally deliver this acidified, organic matter-rich water to Singapore. Localised acidification experienced seasonally by Singapore will likely become more severe in the future with increased carbon dioxide emissions occurring worldwide. The team is collaborating with the UK Centre for Ecology and Hydrology and the Norwegian research centre NORCE, and the analytical capacity will play a key role in the new Marine Environment Sensing Network project, which will collect baseline data across Singapore waters as a long-term monitoring initiative.

Monsoon-driven changes are also observed in concentrations of dissolved nutrients in Singapore, which vary from barely detectable to moderately eutrophic levels. MSRDP-P11 took advantage of this variability to advance our understanding of nutrient cycling on coral reefs. There is year-round high phosphorus cycling activity on Singapore's reefs, to which corals themselves contribute substantially—this may, in part, account for nitrogen limitation usually experienced in coral reefs. The team also showed that a diverse community of coral-associated microbes fixes inert nitrogen gas into bioavailable nitrogen, with the microbial community in the coral skeleton playing a particularly large role. This project also provided updated estimates of sedimentation rates for two reefs in Singapore, and showed that slower water movement at deeper depths allows much higher net sediment accumulation than at the reef crest, which likely helps to limit the depth distribution of corals.

To assess the impacts of ocean acidification, it is critical to understand the basic biology of calcium carbonate production. Most research has so far focused on corals, and we have a much poorer understanding of calcium carbonate production by other organisms. MSRDP-P22 studied the calcification process in the fluted giant clam, *Tridacna squamosa*, which is widespread on Indo-Pacific reefs. Like corals, this species attains a high growth rate by harbouring symbiotic algae (zooxanthellae) in its colourful outer mantle. The project identified several genes that help the clams to take up dissolved carbon from seawater and supply it both to their symbiotic algae to support photosynthesis, and to their extrapallial fluid where the carbon forms new calcium carbonate shell. The team measured how these carbonic anhydrase and proton-transporter genes are expressed in different parts of the clam tissue under different light conditions. This knowledge is critical to assess how the physiology of giant clams responds to ocean acidification and other environmental changes.


Marine biodiversity enhancement tiles at Changi Bay

Investigating biodiversity

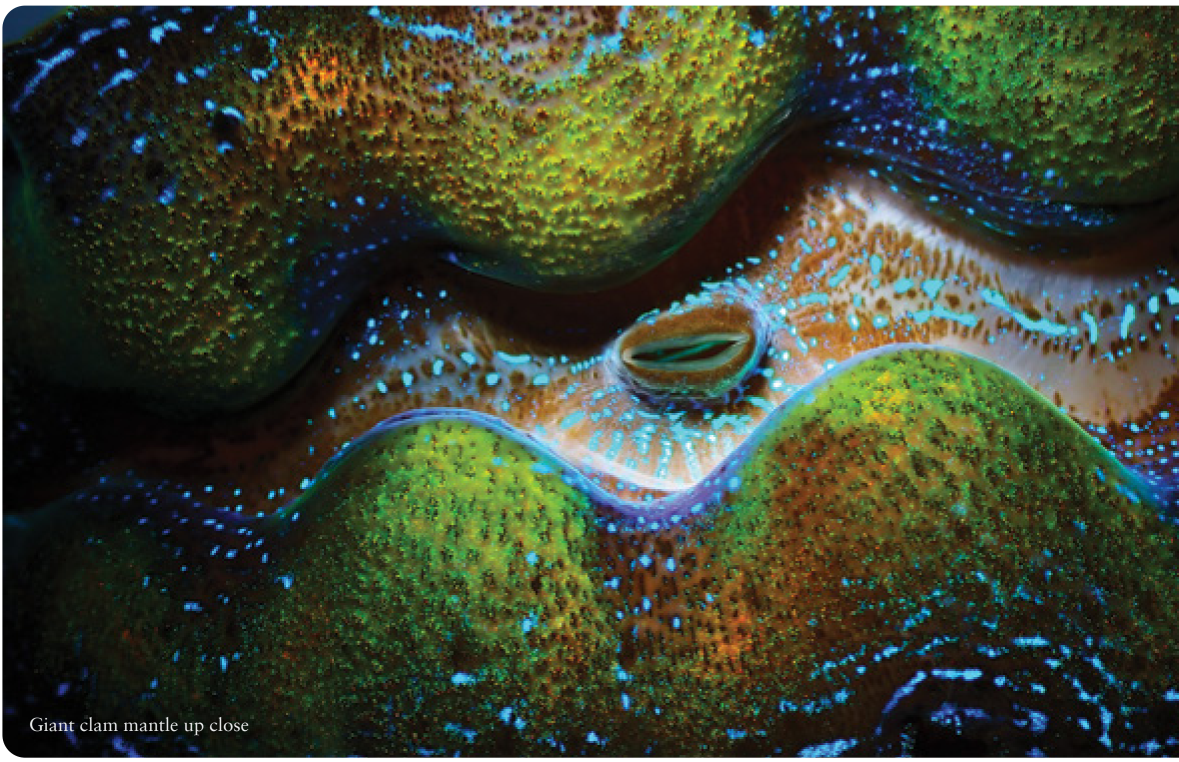
By virtue of its location at the edge of the Coral Triangle, Singapore harbours very high marine biodiversity. To inform management and use of our marine ecosystems and resources, this biodiversity must be properly characterised and monitored, and the ecological functioning of marine communities understood. Biodiversity-related projects across the MSRDP domains ranged from fundamental investigations aiming to better assess local biodiversity to bioprospecting studies that explored the potential for technological exploitation.

Several projects addressed the biodiversity of animal groups that had so far been relatively neglected. MSRDP-P18 created a comprehensive DNA-based inventory of fish diversity. Together with international and local experts and volunteers, the team collected more than 10,000 specimens across Singapore, representing two classes, 27 orders, 97 families, 257 genus, and 500 species, based on morphology and genetic barcoding. Importantly, this DNA barcode library now allows fish diversity in Singapore to be assessed and monitored using environmental DNA in water samples. As a proof of concept, the team analysed fish DNA recovered from water samples at 17 sites, detecting 250 fish species. This project has thus created important foundational knowledge to facilitate long-term monitoring of fish diversity across Singapore.

Two projects examined horseshoe crabs, an ancient lineage with only four species—two of which are found in Singapore. They are ecologically and economically important, providing *Limulus* amoebocyte lysate for endotoxin analysis across the pharmaceutical industry. MSRDP-P41 used population genetic analyses to show that the three Asian horseshoe crab species have different population expansion histories over the last glacial–interglacial period of sea-level rise across the Sunda Shelf. MSRDP-P19 focused on the two species living in Singapore (the mangrove horseshoe crab and the coastal horseshoe crab). Tagging and monitoring revealed relatively little movement of the horseshoe crabs, while the genetic analysis indicated a sharp decrease in population size around 60,000 years ago. Unexpectedly, the horseshoe crab lineage was found to have undergone three whole-genome duplications, with several immune-system genes having further expanded through tandem duplications—potentially a factor in the high sensitivity of their immune systems. Another key finding is that the mangrove horseshoe crab is likely more vulnerable to loss of genetic diversity and may need to be prioritised for conservation. Future analyses of the data from both projects will allow a better understanding of the adaptive and immunological importance of different genes.

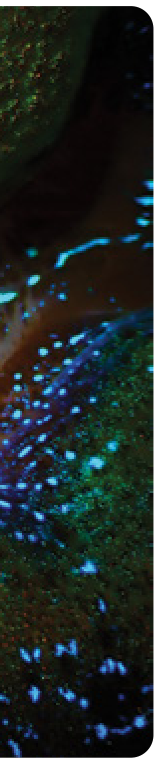
A less well-known, but still fascinating group are the sea-skaters of the genus *Halobates*. They are one of very few insect groups that are truly marine, and one of very few marine taxa that are specialised to live at the air–water interface. MSRDP-P47 sequenced the genome of several *Halobates* species, and is currently in the process of assembling and annotating the data, which represent the first-ever genomic data for marine insects. Because *Halobates* is characterised by several unique adaptations to enable the unusual lifestyle of this group, a full analysis of the genomic data will provide important clues about how *Halobates* has managed to expand from coastal populations across the world's open oceans.

The reach of MSRDP's biodiversity investigations extended well beyond animals to the microbial level. Aside from the aforementioned coral microbiome research under MSRDP-P03 and MSRDP-P11, the diversity of marine viruses and plankton was addressed by MSRDP-P13. This project developed a rapid and accurate identification method for phytoplankton species using Oxford Nanopore's MinION third-generation sequencing technology, which can be used to characterise the species composition of phytoplankton blooms in Singapore. This rapid and simple technology



Giant clam mantle up close

Moon crab
(*Ashtoret lunaris*)



can potentially be employed to warn aquaculture operators of an incipient harmful algal bloom. The project also showed that the viriome (i.e., the collective biome of viruses) in Singapore varies, as different viruses use different ecological strategies according to the availability and growth of different species of host microbes, which may influence the course of phytoplankton blooms in Singapore. Further work is underway to better understand the dynamics of phytoplankton blooms in the Johor Strait, and to develop an innovative solid-state PCR method to analyse RNA viruses.

While biodiversity is of critical ecological importance, it also provides technological opportunities for exploitation, especially as a potential source for novel bioactive chemicals. MSRDP-P15 and MSRDP-P34 explored properties of metabolite chemicals produced by marine cyanobacteria and by bacteria associated with marine sponges. The team integrated genomics, analytical chemistry, and biological screening, and discovered 40 strains of microbes that produce metabolites that inhibit quorum sensing by the human pathogen *Pseudomonas aeruginosa*. Quorum sensing is used by bacteria to control phenotypic behaviour, e.g., to form biofilms and cause disease in humans. Further analysis led the team to discover novel classes of cyclic peptides, including the trikoramides, and to show that they inhibit quorum sensing and have anti-cancer activity in cell lines. The team is using further computational and experimental techniques to identify more novel compounds, and is applying for new funding to study the detailed mechanism of action of these chemicals, as well as the capacity for antimicrobial activity *in vivo*.

Magnetotactic bacteria (MTB) biomineralise iron to form magnetite and/or greigite, and contribute disproportionally to the biogeochemical cycling of iron in marine ecosystems. However, the diversity of MTB in equatorial Asia, where the earth's magnetic field is weak, was previously unexplored. Using bioinformatic analyses, MSRDP-P30 investigated MTB in seafloor sediments in Singapore. The genera *Magnetovibrio* and *Desulfamplus* were the dominant MTB, but metagenomic analysis showed that most taxa could not be classified to species level. Overall, the relative abundance of MTB was substantially lower than in other regions. These findings will facilitate future research efforts to unravel the ecological roles of MTB in tropical marine environments, as well as bioprospecting of tropical MTB lineages for biotechnological applications.

The need to safeguard marine biodiversity also poses the significant challenge of how to measure and monitor biodiversity. Traditional approaches rely on visual surveys by divers, which are expensive, labour intensive, yield very limited data sets, and are challenging in low-visibility environments such as those of Singapore's waters. MSRDP-P20 sought to overcome these limitations by developing technology to passively monitor reef biodiversity by recording underwater sounds. Many reef-dwelling organisms produce sounds, and the complexity of the soundscape of a reef is correlated with reef biodiversity. In an urbanised setting such as Singapore's, acoustic monitoring is particularly challenging because of human noise such as ship traffic. Nevertheless, 1.4 million episodic noise signals were identified as biological, and the team used machine-learning techniques to develop a measure of sound richness that can be used to quantify biodiversity differences. Interestingly, this measure varies by 30% between reefs in Singapore. This approach also has the potential to yield insights into the impact of human noise pollution on reefs, and to provide approaches to mitigate such impacts.

New technologies and platforms

Advances in marine science and environmental management hinge critically on developing new technologies, and platforms to manage huge volumes of research data effectively. The MSRDP funded several projects dedicated largely towards such technological advances.

MSRDP-P12 developed new technologies to study microbially induced corrosion. Metal structures such as pipelines corrode in seawater, and microbial biofilms can greatly accelerate this process. The project team developed a novel high-pressure incubation chamber that can take electrochemical measurements to monitor corrosion in real time under simulated deep-sea conditions. They also participated in several sampling expeditions to collect deep-ocean microbes involved in corrosion. The team has filed a technology disclosure for their incubation system and has won a follow-up grant through NRF's Competitive Research Programme with two major private-sector companies, Exxon-Mobil and Keppel Offshore.

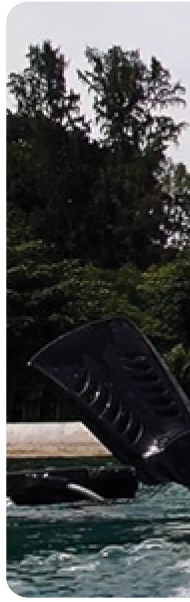
Marine organisms not only drive corrosion of underwater infrastructure but also create serious problems by growing on, or 'biofouling', underwater structures. Project MSRDP-P29 further developed a promising technology, Slippery Liquid-Infused Porous Surfaces (SLIPS), by testing environmentally friendly infusion liquids. The team worked with industrial collaborator Adaptive Surface Technologies (AST) and developed successful bio-inspired and non-toxic coatings. The research also generated new fundamental insights into the properties that determine the success of antifouling coatings, and into the properties of adhesive proteins produced by various fouling organisms. The team has also strengthened collaborations with the Housing and Development Board (HDB), and industry partner ISOTeam Ltd, to test the coating on a solar energy installation near Woodlands. This trial yielded promising results, paving the way for further partnerships with HDB, AST, and ISOTeam.

Project MSRDP-P28 took a different approach to tackling biofouling, by investigating whether mechanically straining metal can render its surface sufficiently hydrophobic to prevent biofouling. After showing that the application of a mechanical strain can render steel and aluminium surfaces permanently more hydrophobic, the researchers determined that the mussel *Mytella strigata* attaches less to strained metal surfaces than to controls. The team is planning to file for a patent and is seeking further funding to develop this technology, which may have further applications in medical devices and even carbon dioxide capture.

Accurately and rapidly detecting harmful microbes is a major challenge in the field of environmental monitoring. While this can be done easily in well-equipped laboratories, it is very time-consuming and expensive. Project MSRDP-P01 developed a microfluidic Lab-On-Smartphone platform that quantifies harmful bacteria and algae rapidly in the field. The system uses microfluidics and is attached to a smartphone, and can detect target microbes in minutes in the field using cell-staining and PCR-based approaches. The team is now seeking to further develop this technology to detect food-borne pathogens using a similar platform.

Monitoring harmful algal blooms was also the focus of MSRDP-P21, which sought to develop a prototype sensor to detect algal toxins. The team synthesised polymers with a molecular imprint of an analogue of the toxin molecule with common recognition features. It is expected that the molecular imprint will recognise the toxin, so that when the toxin binds to the polymer a sensor response is triggered. Using the diatom-produced toxin domoic acid as the target toxin, the team developed sensors based on both quantum-dot phosphorescence and electrochemical detection principles. While the quantum-dot sensor was promising in laboratory tests, it performed poorly in seawater. In contrast, the electrochemical sensor showed promise, but needs further development to optimise sensitivity and reproducibility.

Technology development extended all the way to sea-level research. A key determinant of sea-level rise is the rate of glacier melting. MSRDP-P42 developed a passive-acoustic approach, exploiting the fact that the explosion of air bubbles



Real-time monitoring buoy at Bendera Bay, St. John's Island

caused by ice melting underwater produces sounds similar to frying bacon. Together with Scripps Institution of Oceanography and the Polish Academy of Sciences, the project team collected acoustic data in Svalbard, Norway, and gained insights especially into the depth-dependence of the sound signal. These results are an important foundation for building a long-term monitoring system to estimate glacier melt rates, and to this end the team is further studying the acoustic distortions created by salinity and temperature gradients in the water, and the physics of air bubbles released by melting ice.

A fundamental data set to support any marine science programme is an accurate bathymetry, i.e., a map of water depth. Acquiring accurate bathymetric data at high resolution requires highly specialised equipment and data processing, and MSRDP-P46 collaborated with the Maritime and Port Authority (MPA) to create an updated and enhanced bathymetry for Singapore. Presently, the team is seeking publication permission from MPA so that the data can be made available to the wider research community in Singapore.

Finally, three projects focused on data and knowledge-sharing platforms. MSRDP-P08 and MSRDP-P40 created and maintained the Marine EnvironmenTal Information System (METIS) database, which is a new cross-disciplinary data management platform for marine science data. METIS enables researchers to upload their data, and access and visualise the data provided by other projects using the embedded mapping and graphing features. The METIS team is currently reviewing the feasibility of integrating the METIS data into the database being created by the Marine Environment Sensing Network project, so that a national-level data-sharing platform for marine science in Singapore can be created. MSRDP-P44 examined the feasibility of extending this work back into the past by accessing non-digitised data and data from grey literature. The project identified quite substantial amounts of data going back to the 1980s and 1990s across Southeast Asia, and concluded that digitising these data and harmonising the associated metadata is feasible. Further efforts would be needed to automate some of this work for greater efficiency, but the project showed that this approach has great potential to make historical data sets across the region available. This would be especially valuable for determining environmental baselines with limited human disturbance.

Fostering education and outreach

Achieving the MSRDP objectives required strengthening of marine science education and outreach. Three projects (MSRDP-P35, -P36, and -P37) were created for student involvement in research. The Explore grants (P35) allowed students from junior college to undergraduate level to pursue six-month research projects at the St. John's Island National Marine Laboratory. A total of 44 students participated, covering topics spanning all the MSRDP domains. Several of these students have published their work or are preparing manuscripts for international journals, and students presented their work and networked during the Young Marine Scientist Symposia in 2019 and 2021. The Overseas Student Programme (P36 and P37) allowed undergraduates from Nanyang Technological University and National University of Singapore to undertake research visits of six to 12 weeks to marine research institutions overseas. While the COVID-19 pandemic cut this programme short, a total of 38 students visited institutions in North America, Europe, Asia, and Australia. Research topics spanned the range of MSRDP domains, and a number of publications have arisen from the research. On the basis of feedback received, the students found the experience enriching and rewarding, and some have gone on to take up marine-related graduate studies.

Many of the MSRDP projects undertook their own outreach, but there were also several larger outreach events that multiple projects participated in. In total, over 120 outreach events that included public seminars, school talks, guided walks, workshops, and roadshows were conducted under the MSRDP.

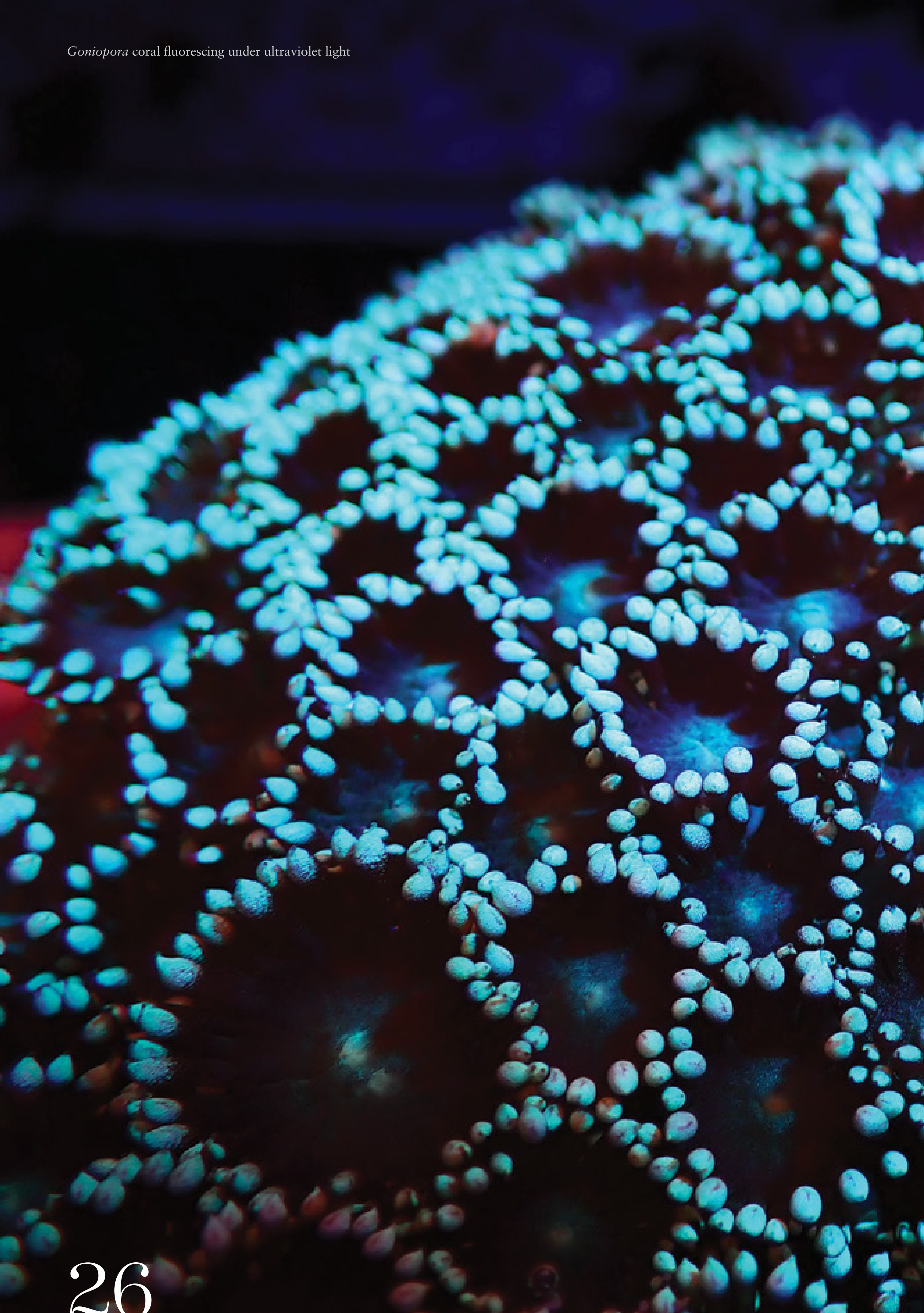
Climate-controlled aquarium at SJINML

Marine science at St. John's Island

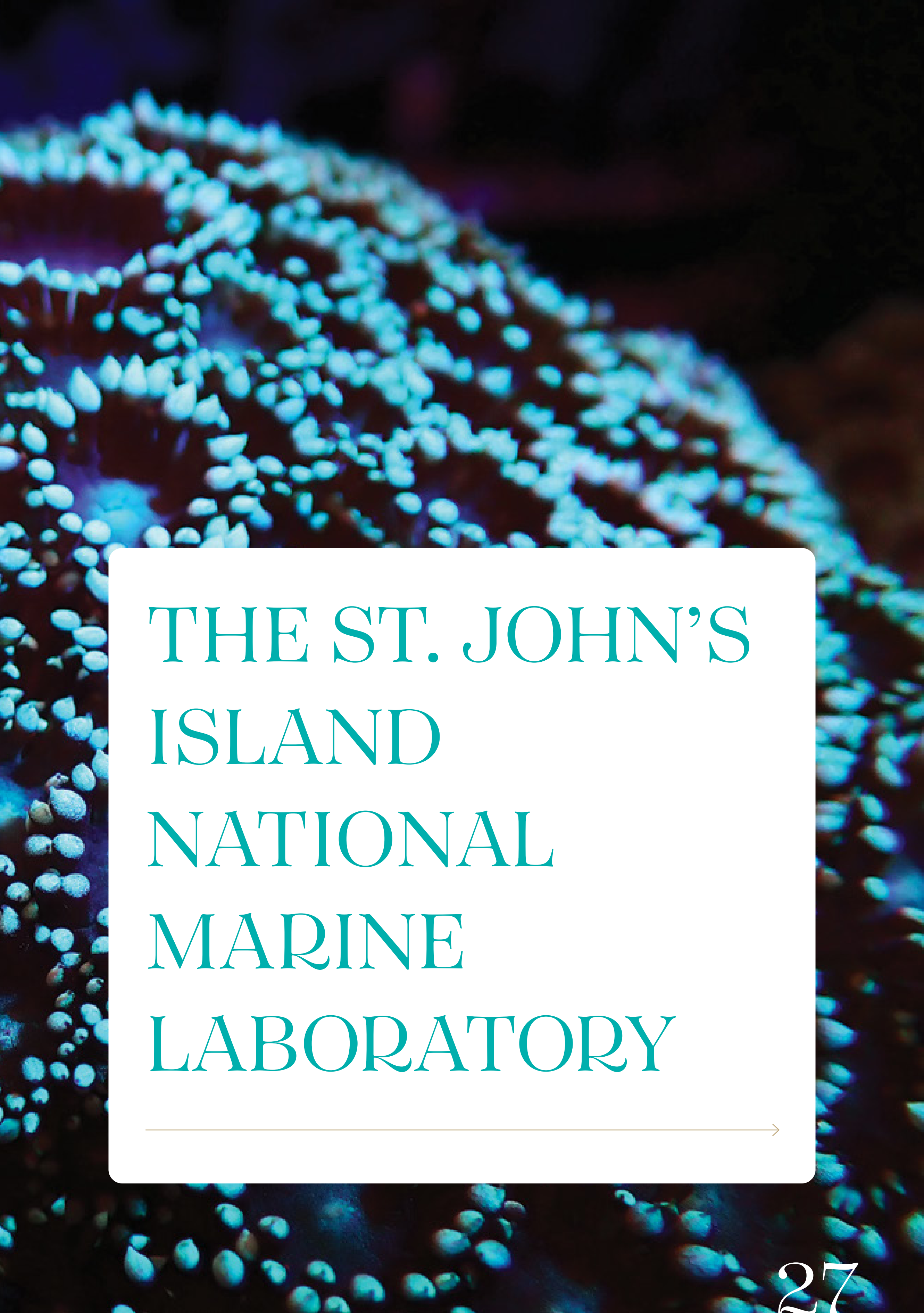
A key facility that supported and complemented the MSRDP is the St. John's Island National Marine Laboratory (SJINML). This facility is part of the National Research Infrastructure and is funded by NRF. For many of the MSRDP projects, part of the research was conducted at the island, including dozens of student-led studies supported by student grants from MSRDP-P35. Through project MSRDP-P07, SJINML has also established a core resource of native model organisms that allows researchers to use native, tropical animal models for their work. This is particularly important for environmental impact studies, because results obtained with model organisms from other climate zones do not necessarily apply to tropical species. Importantly, the supply of cultured model organisms by SJINML ensures that research can be conducted without impacting Singapore's already-degraded marine habitats. Realising the potential for the St. John's Island Complex (SJI-C, consisting of the merged St. John's, Lazarus, Seringat, and Kias Islands) to play a pivotal role in research, education, and innovation in Singapore and beyond, MSRDP-P43 delivered a comprehensive integrated concept plan with a vision to establish SJI-C as Islands of Eco-innovation. This project identified opportunities for SJI-C to strengthen Singapore's marine science R&D, environmental education, and test-bedding cutting-edge green and blue innovations, to position Singapore as a global leader in sustainable development and the Green/Blue Economy. At present, the SJI-C Review and Recommendations document continues to be circulated to more stakeholders (including civil society) and is being updated by the MSRDP-P43 team. It will be an important document for upcoming plans by the Urban Redevelopment Authority (URA) and Sentosa Development Corporation (SDC) to develop the southern islands in a sustainable manner.

Singapore as an island nation is both literally and metaphorically shaped by the sea and its maritime heritage. A strong base in marine science is essential for cataloguing and protecting biodiversity, ensuring sustainable use of marine ecosystems and continued supply of valuable ecosystem services in the face of global change. It can also lead to new products and services at the engineering and social science interfaces. It was a great pleasure to be invited to be involved in the MSRDP in 2016 and to be able to assess the considerable progress made by the funded projects in a mid-term event in 2018.

Stephen John Hawkins
Professor Emeritus
Ocean and Earth Science, National Oceanography Centre Southampton, University of Southampton, UK
Lankester Research Fellow, Marine Biological Association of the UK, Plymouth



Goniopora coral fluorescing under ultraviolet light



THE ST. JOHN'S ISLAND NATIONAL MARINE LABORATORY

Contributed by Jani TI Tanzil and Serena LM Teo

SJINML on St. John's Island

The marine laboratory at St. John's Island was established in 2002 as a facility for interdisciplinary marine research. In 2016, the National Research Foundation designated the facility as the St. John's Island National Marine Laboratory, a National Research Infrastructure (NRI) to support strategic marine science research in Singapore.

The **St. John's Island National Marine Laboratory** is Singapore's only offshore marine station. Operated as an NRI since 2016, SJINML supports multidisciplinary and multi-institution marine science research.

The mission of SJINML is to

1. Enhance the quality of national marine science research by facilitating multidisciplinary research interactions through provisions of quality access to research expertise, facilities, and specialist training support
2. Conduct research that supports national agencies for projects of strategic significance
3. Increase high-impact research outputs in sustainability research
4. Catalyse collaborations that enhance strategic national and international research programmes
5. Implement manpower training programmes to support future national needs in marine science

St. John's Island National Marine Laboratory

Beginning with the visit to Hawai'i by National Research Foundation CEO Teck Seng Low, Programme Director George Loh, and coral biologist Loke Ming Chou in 2015, I had the pleasure of stressing to the group the international importance of Singapore to marine biology. Because of Singapore's strategic location at the confluence of two oceans, it was, to me, imperative that the St. John's Island Marine Laboratory be strongly supported and augmented. It is the only truly active marine lab within a thousand kilometres and admirably situated in the Singapore Strait. I thus found it gratifying to learn in 2016 that the NRF has established the Marine Science Research and Development Programme and provided it with sufficient funds to make a significant impact on marine science in Singapore.

Michael G. Hadfield
Professor Emeritus
Pacific Biosciences Research Center
University of Hawai'i Manoa,
Department of Biology

Coral spawning at Raffles Lighthouse

With an urgency to address climate change, SJINML's mission has grown to embrace issues such as the resilience of Singapore's coastal environment, the blue economy, eco-engineering, climate adaptation, and food security—all to uphold Singapore as a sustainable, yet vibrant island nation. With the Tuas mega port and fish farming expanding southwards in the coming years, there will be increasing demands for sustainable development of Singapore's 'southern front'. SJINML is strategically placed to support both our scientists and environment managers in this endeavour.

SJINML is Singapore's only fully equipped offshore science research laboratory. Since 2020, the marine station has been further upgraded to include: a state-of-the-art climate-controlled aquaria for climate change research, biosafety-level-2 facilities to support upcoming disease- and pathogen-focused research, a 10m seawater current flume to aid studies in marine hydrodynamics, and laboratories that enable researchers to conduct biochemistry and genetic work or take high-resolution bio-imagery. Backed by a team of trained and skilled manpower and a network of stakeholders in research, industries, and agencies, SJINML is well-equipped to remain a focal point for marine science research in Singapore.

Since 2016, SJINML has supported the research of over 250 local and overseas academics and students from 16 institutions and organisations; these include projects under the MSRDP. With a strong student community, SJINML has been beneficial in attracting the next generation to take up marine science–related jobs and careers. SJINML's outreach programmes and partnership with the National Parks Board for the Marine Parks Outreach and Education Center have contributed to increased public awareness of the marine science and conservation in Singapore.

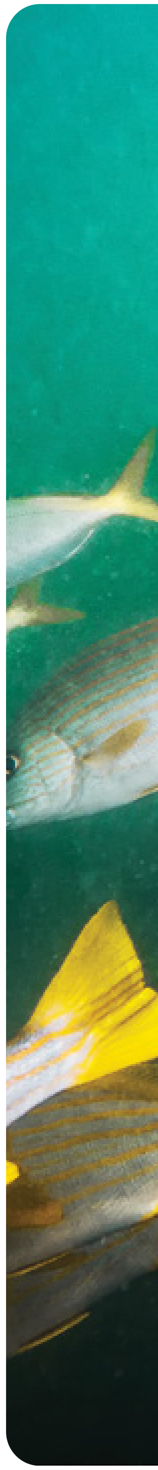
A crucial element in building capacity and capability was the relaunch of the St. John's Island Marine Laboratory as a national facility in parallel with some excellent multidisciplinary and cross-institutional projects. There were some truly excellent projects at the nexus of engineering and natural sciences with strong societal relevance. These projects also boosted the careers of numerous locally based, early-career researchers as post-docs, PIs, and Co-Is.

Stephen John Hawkins
Professor Emeritus
Ocean and Earth Science, National Oceanography Centre Southampton, University of Southampton, UK
Lankester Research Fellow, Marine Biological Association of the UK, Plymouth

An exposed intertidal reef in the Singapore Strait

THE SINGAPORE BLUE PLAN 2018

Contributed by Zeehan Jaafar, Jani TI Tanzil, Nicholas WL Yap, Danwei Huang, Yan Xiang Ow



The Blue Plan is a ground-up initiative that presents the vision of the marine community in Singapore and is presented to the Singapore government every decade. The Singapore Blue Plan 2018 (SBP 2018), the third instalment of the Blue Plan, is a proposal for the conservation of coastal and marine ecosystems, led by marine biologists and prepared with the broad inclusion of over 100 academics, environmental lawyers, and stakeholders.

The SBP 2018 proposed six multifaceted recommendations advocating for the conservation of marine ecosystems, the sustainable use of marine resources, and government–stakeholder partnerships. Along with these recommendations, summaries on the current state of knowledge on the diversity of marine organisms and habitats, and an overview of the relevant legislation governing marine ecosystems and resources were included.

The Marine Science Research and Development Programme was instrumental in the capacity building that resulted in the SBP 2018. All members of the editorial team and more than a quarter of the contributors were supported by the MSRDP; and information arising from the research funded under the MSRDP contributed to the SBP 2018.

Towards sustainable conservation of coastal and marine ecosystems

Singapore's marine environment provides valuable ecosystem resources and services. Intensive urbanisation over several decades has resulted in extensive modifications to our natural coastlines and marine areas. Yet, rich marine biodiversity persists in the remaining natural habitats.

Singapore's marine environment, and diversity therein, face stressors at the global, regional, and local scales. The variability in the interaction outcomes of global and local threats is unprecedented. To mitigate impacts of rapid environmental changes, active conservation, effective management, and restoration measures are increasingly necessary.


Sweetlips in Singapore waters (*Plectorhinchus chrysotaenia*)

The SBP 2018 proposes six recommendations to conserve coastal and marine ecosystems with integrated and sustainable strategies:

1 Establish formal management systems for marine environments

The SBP 2018 encourages the establishment of a spatial planning regime that incorporates international standards for marine areas. Legal provisions for Strategic Environmental Assessments (SEAs) and environmental impact assessments (EIAs) are to be considered, especially for ecologically sensitive areas. Efforts must focus on the monitoring of key components of coastal and marine biodiversity and ensure that these reports, and records, are publicly accessible to promote greater transparency and accountability in environmental governance.

2 Provide sustained funds for research initiatives and long-term monitoring programmes

The field of marine sciences has benefitted greatly from funds from the National Research Foundation's MSRDP, as well as the Technical Committee for Coastal and Marine Ecosystems (TCCME). Sustained funding support is crucial to effectively maintain, monitor, and manage marine habitats and native biodiversity. The SBP 2018 also recommends establishing long-term monitoring programmes that allow for open-access basic water quality and baseline data to support research.

3 Enhance legislation to protect marine biodiversity and environment

The SBP 2018 recommends updating existing legislation and administrative practices to include the protection of marine organisms and marine habitats, regulation for the use of marine spaces, and clamping down on the sources of pollution.

4 Improve intra- and inter-agency coordination of public marine database

A well-coordinated intra- and inter-agency public database on marine biotic and abiotic parameters can help streamline processes among stakeholders for the effective management of marine areas and resources. Regular dialogue among agencies and stakeholders can harness the collective knowledge to forge towards improved understanding of the processes within our marine areas, and apply information pertinent for the conservation of marine resources.

5 Protect remaining natural marine habitats from unnecessary biodiversity loss

The SBP 2018 recommends that all existing natural marine areas are accorded protection from further development to conserve refugia for marine organisms. Marine habitats in Singapore are small and fragmented but each site is unique and can host high biodiversity. Protection of habitat types cannot be reduced to a single exemplary site, and must be extended to be as exhaustive as possible.

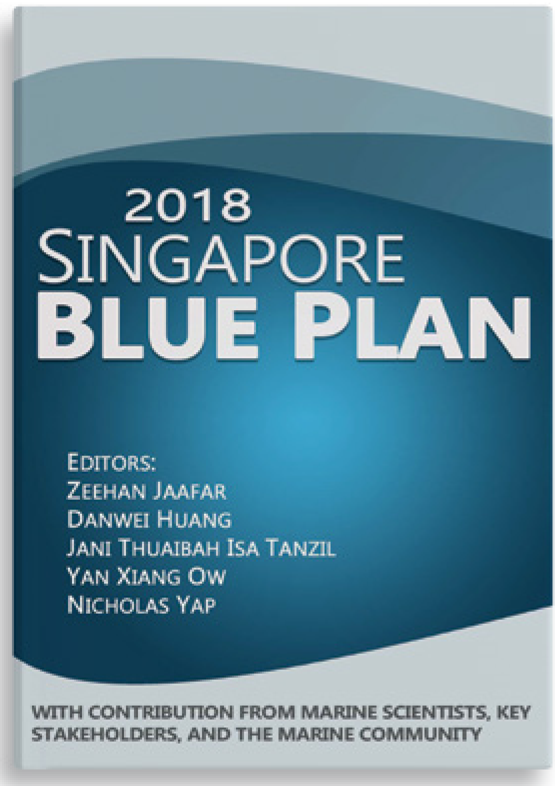
6 Incorporate topics on natural environment into school syllabuses and promote science communication

Education is key to conservation efforts and the SBP 2018 recommends incorporation of basic concepts of environmental sustainability into formal school curricula.

SBP 2018

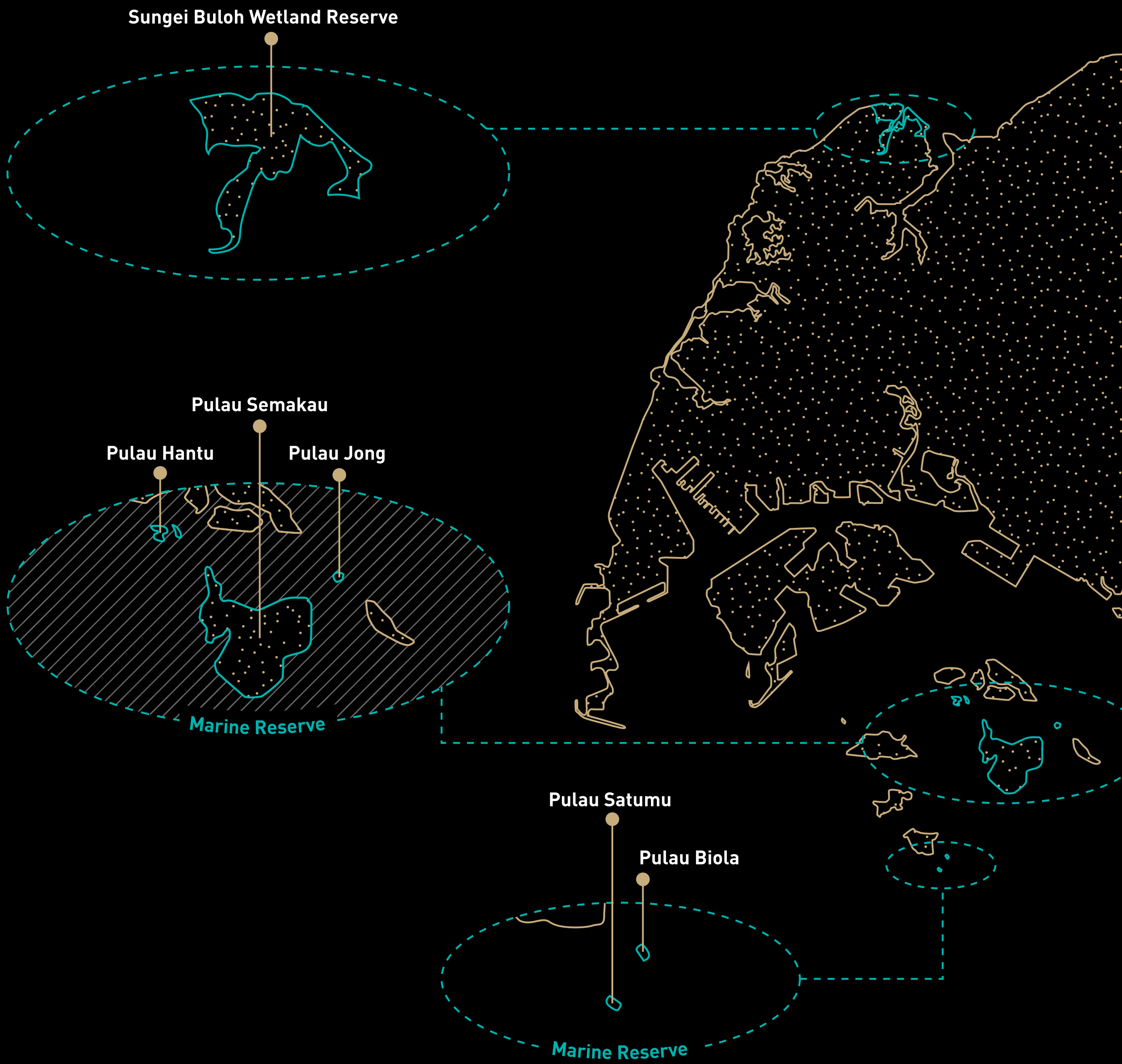
The SBP 2018 was launched on 13 October 2018, in conjunction with International Year of the Reef, by Desmond Lee, then Minister for Social and Family Development and Second Minister for National Development. Since its launch, contributors have been involved in many outreach activities such as penning public commentaries and blog posts, giving talks at public events and to government agencies, as well as participating in roadshows and carnivals so as to share the contents of the Plan with members of the public. A workshop was also held to discuss with interested members of the public the road map to realise Recommendation 6—promotion of science communication.

The SBP 2018 recommendations are publicly shared so that citizens may use them as guides to steer conservation and education outreach programmes. The recommendations are truly reflective of the concerns of stakeholders and government agencies. This is exemplified by the gazette of Mandai mangrove and mudflat as a nature park a few days before the launch of the SBP 2018—in line with Recommendation 5 to expand the boundaries of Sungei Buloh Nature Reserve for protection. In the MSRDP project *Horizon mapping: an integrated concept plan for St. John's Island*, SBP 2018 recommendations were considered in the formulation of future plans for the St. John's Island Complex. In line with Recommendation 2—sustained funding for long-term marine monitoring to support research—a proposal for a Marine Environment Sensing Network for Singapore was put forth in 2019, and funded in 2020 as a five-year project with plans for it to be part of the St. John's Island National Marine Laboratory as a National Research Infrastructure.



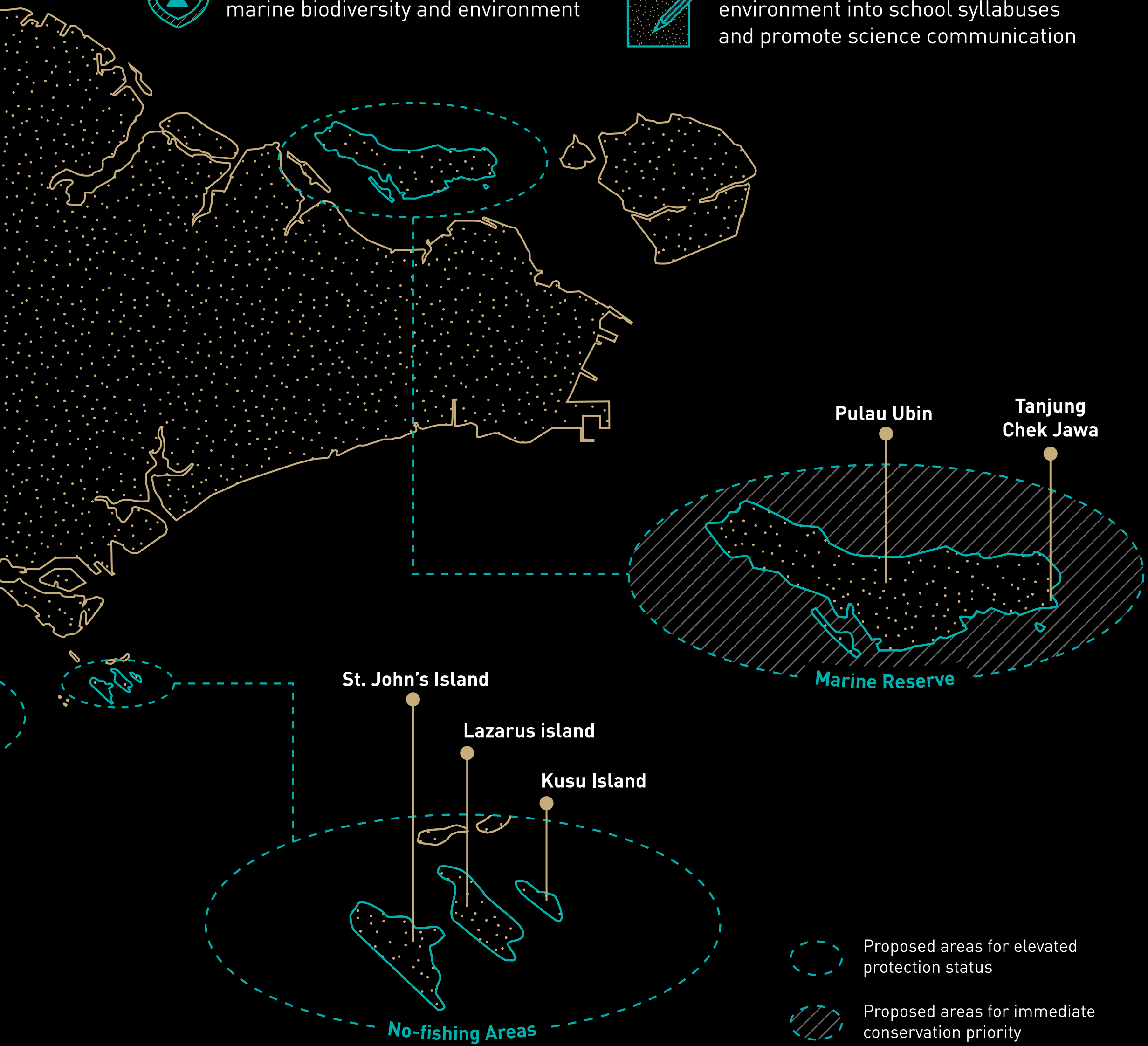
The SBP 2018 is published by the Singapore Institute of Biology. Access the full document here: sibiol.org.sg/publications/the-singapore-blue-plan.

PROTECTING OUR NATION'S MARINE LANDSCAPE

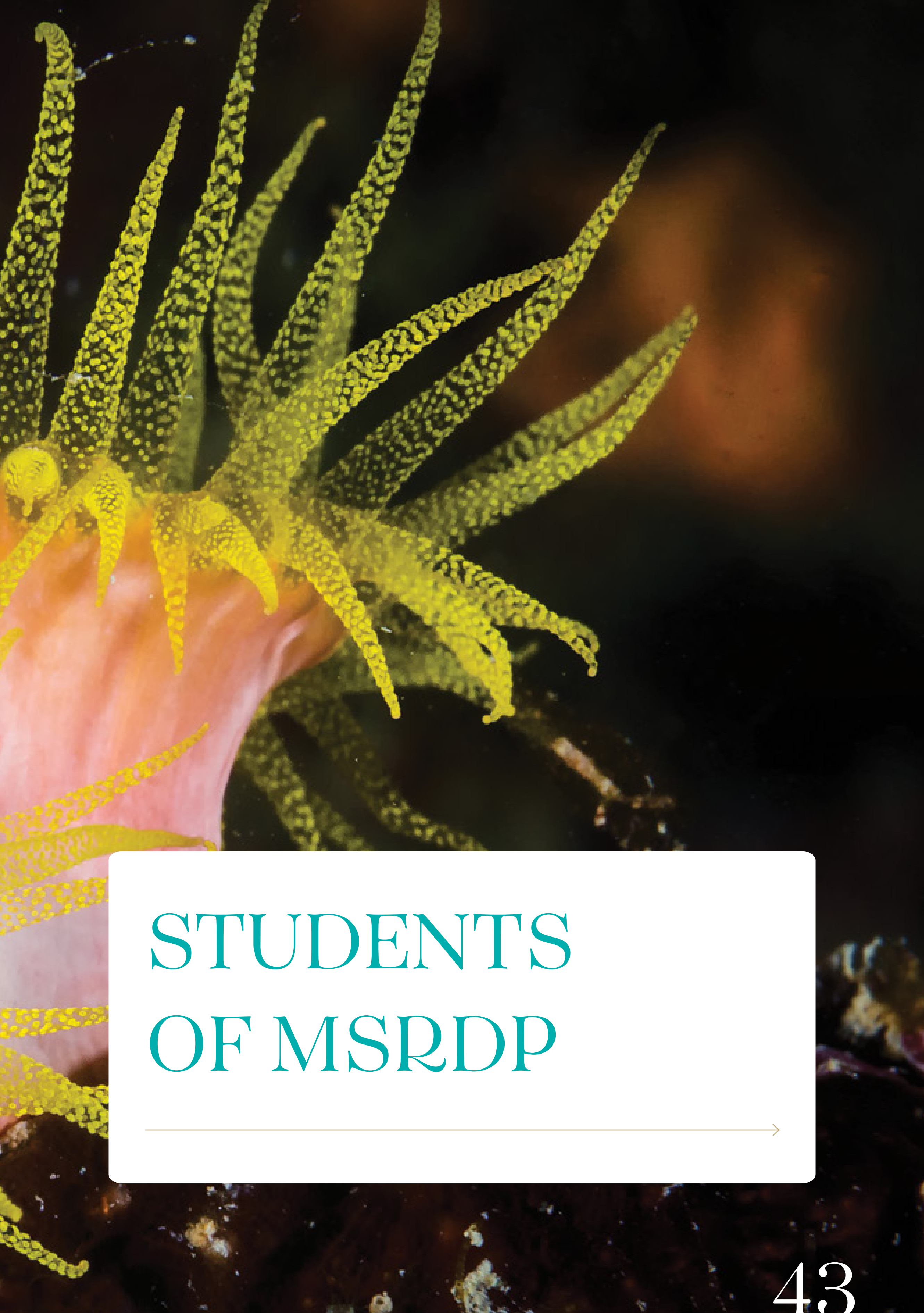


Six recommendations to conserve coastal and marine ecosystems with integrated and sustainable strategies

- Establish formal management systems for marine environments
- Improve intra- and inter-agency coordination of public marine database
- Provide sustained funds for research initiatives and long-term monitoring programmes
- Protect remaining natural marine habitats from unnecessary biodiversity loss
- Enhance legislation to protect marine biodiversity and environment
- Incorporate topics on the natural environment into school syllabuses and promote science communication



Cave coral (*Tubastrea* sp.)



STUDENTS OF MSRDP

PHD SCHOLARS

Looking towards the future, the MSRDP was aware of the need to build up a robust base of newly-trained marine scientists familiar with local and regional challenges. To achieve this, the MSRDP provided funds to support nine PhD scholarships dedicated to marine research and development. This has created a pool of talent that can contribute to the many new projects the MSRDP catalysed and help drive forward marine science in Singapore.

Scholar

Christaline George

What was your PhD topic?

My PhD topic is *Long-read Nanopore Metabarcoding : The future of algal bloom detection & environmental monitoring*.

What were the most interesting findings from your research?

My research led to the development of a methodology which enables the rapid and precise identification of microalgal species using the MinION sequencer from Oxford Nanopore Technologies. This methodology can detect the relatively dominant microalgal species in a sample and even those present in extremely low concentrations at even 1cell/mL. Hence, this methodology can be used to monitor the trends of microalgal diversity and potential harmful algal blooms (HABs) in our coastal waters. The phenomenon of HABs has been an alarming concern for the tropical waters of Singapore, causing significant economic losses to the fishing and aquaculture industries. This approach holds promise for the early detection of HABs even in the most remote locations where expensive laboratory facilities and professional expertise are not readily available. Thus, providing avenues to improved forecasting and mitigation.

What new experiences did you gain?

I have gained invaluable experiences during the four years of my PhD, both academic and practical. Experiences gained from my fieldwork are essential skills for any marine scientist which includes planning and carrying out sampling at sea, troubleshooting and adapting to any technical issues during sampling, and many others. Having the ability to communicate science with simplicity is as important as carrying out research of a high standard. I did acquire some crucial techniques through the scientific communication module at NTU which makes presentations and scientific writing very effective. Fulfilling my teaching assistant

I have gained invaluable experiences during the four years of my PhD, both academic and practical.

duties during overseas field trips has been a truly refreshing experience with respect to interacting with students, coordinating activities, sharing knowledge as well as learning and understanding from their perspective. Although taking a PhD is a singular task, it encompasses a lot of team-work and collaboration which has taught me to adapt. The academic suite of knowledge gained during these four years, some of which were unplanned and multidisciplinary, made this entire journey very holistic.

What do you think are the key remaining questions in your field of marine science?

One of the areas that should be investigated actively in our coastal waters are the impacts of climate change and eutrophication on phytoplankton communities on a long-term basis. As they form the base of the marine food-web, changes in their community structure would impact the rest of the ecosystem. More long-term research should be dedicated towards understanding the nature of HAB events and their causes in our coastal and warm waters.

What are one or two other key areas that should be prioritised for funding?

Research funding should consider allowing longer sampling regimes (i.e., more than two years) as this will provide important insights to the long-term impacts of any phenomenon or condition under study. More resources should be allocated for travel, outreach, and commercial/industrial applications which could provide new avenues of application and development for existing research work.

Scholar

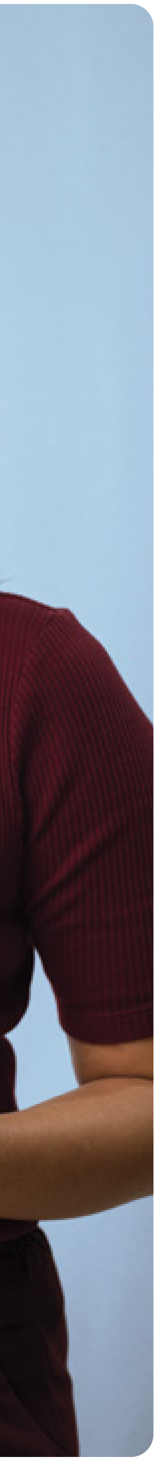
Ma Yadanar Phyo

What was your PhD topic?

My PhD thesis was focused on discoveries of bioactive secondary metabolites from marine cyanobacteria, which was part of an overall MSRDP project (i.e., P-15: *Genomic and metabolomic approach to the discovery of functional metabolites from marine actinomycetes*).

What were the most interesting findings from your research?

I discovered a class of compounds from local marine cyanobacterium, which was cytotoxic towards three cancer cell lines (i.e., breast cancer and two leukaemic cell lines). One of the compounds also expressed a dose dependent quorum sensing inhibitory activity. Quorum sensing is a communication mechanism that bacteria use to relay messages (i.e., gene expression) to others in a population; this may result in the bacteria strain becoming more resistant to a certain therapeutic drug as a more beneficial phenotype results. Therefore, the presence of such a compound inhibiting the communication within/among the bacteria colonies could potentially suppress microbial infections and multidrug resistant bacteria.



> Given that my academic background was mainly in chemistry, this PhD provided a new experience in a different field: biology.

What new experiences did you gain?

Among a range of new experiences was the handling of complex machines, conducting biological assays, and developing my analytical skills. As I am working on isolating pure compounds from marine cyanobacteria, I needed to be trained in using HPLC machinery and develop my finesse in isolating the various targeted compounds. Given that my academic background was mainly in chemistry, this PhD provided a new experience in a different field: biology. Lastly, the skills I have gained through this PhD enabled me to analyse the large quantities of data needed to solve compound structures and their stereochemistry.

What do you think are the key remaining questions in your field of marine science?

As my research pertains to the discovery of potential bioactive compounds from marine cyanobacteria, one immediate question would be why these cyanobacteria produce these compounds. It would be useful to determine the purpose of these compounds in the ecology of these bacteria. Another interesting question is: how are these compounds biosynthesised in the bacteria? It would be interesting to conduct more mechanistic studies on these compounds.

What are one or two other key areas that should be prioritised for funding?

The following two areas should be prioritised: (1) genomic approaches to discover bioactive metabolites from marine organisms, and (2) chemical ecological studies of marine microorganisms. Knowledge in this area is severely lacking.

Scholar

Peggy PY Tang

What was your PhD topic?

My PhD examines the effects of macroalgae on the coral microbiome and coral-host responses in urbanised reef systems.

What were the most interesting findings from your research?

Each coral species has its own unique microbiome which allows it to respond differently to the various macroalgal species and the kind of interactions. Slight differences in the microbiomes due to variation in location may alter the response towards macroalgal contact as well, in which these differences could be a way for the corals to better adapt to the local environment. Also, the possibility that the interactions between coral microbiome and the zooxanthellae (algal symbionts) may be species specific, but this is still under study.

What new experiences did you gain?

I did quite a bit of hands-on work, like having to plan out my own experiments and build my own tank set-up and having to keep the corals alive, which is vastly different from working in a laboratory. It is a different kind of work environment from what I am used to, but it was a good experience. Knowledge-wise, I learnt quite a lot since I am relatively new to marine research (as compared to my peers who have been doing marine research for many years), its methodology, and what our local marine fauna are.

What do you think are the key remaining questions in your field of marine science?

One is understanding the underlying mechanisms for the interactions between the coral microbiome, zooxanthellae, and the coral host itself in maintaining coral health during stress conditions. Another key question is understanding the mechanisms underlying the selection for the "best-fit" microbial community of the coral microbiome, which would be useful for current research into coral probiotics for enhancing coral resilience towards various stressors.

What are one or two other key areas that should be prioritised for funding?

Two areas that should be focused on are marine microplastics, and their impacts on marine fauna in an urbanised environment; and subsurface microbiology.

Knowledge-wise, I learnt quite a lot since I am relatively new to marine research (as compared to my peers who have been doing marine research for many years), its methodology, and what our local marine fauna are.

Scholar

Robert Scott Nichols

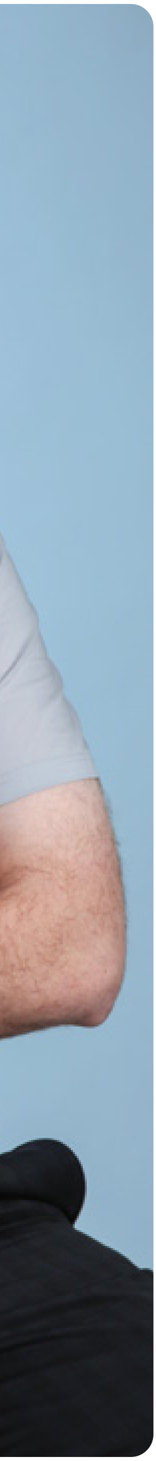
What was your PhD topic?

My PhD topic was on marine biogeochemistry, which is essentially the study of how chemical, physical, and geological processes interact with biology to govern the composition of the natural environment. This is a subject that focuses on a wide range of issues from carbon cycling and global climate to the fundamental processes governing the productivity and resilience of coral reefs, and the projects I worked on were equally diverse. The overall theme is the pathways of dissolved organic matter transformation in tropical coastal waters and consequences of these transformations.

What were the most interesting findings from your research?

Among the many interesting findings from my research, I found that dissolved organic carbon (DOC) from tropical peatlands is resistant to biodegradation in riverine and marine environments—even when nutrients are added to alleviate potential limitations of microbial growth. This suggests that it is inherently resistant to biodegradation and highlights that photo-degradation (i.e., transformation by light) is likely a more important pathway for its cycling.

The next part of my thesis had me investigating the cycling of dissolved organic phosphorus in the coastal waters of Singapore and its corals. Through this I found that alkaline phosphate (AP) activity in both corals and the water column varied little and had no apparent relation to changing environmental conditions over almost two years. This suggests that dissolved organic phosphorus (DOP) cycling was relatively high all year round in the overlying water column, likely contributing to maintaining the nitrogen rather than phosphorus



Among the many interesting findings from my research, I found that dissolved organic carbon (DOC) from tropical peatlands is resistant to biodegradation in riverine and marine environments.

limitation typically reported in coral reef waters. We also found that the enzyme activity associated with corals can potentially cycle as much DOP as several metres of overlying water, highlighting their potential importance to reef phosphorus cycling.

Finally, I examined biogeochemical responses of coastal plankton to ocean acidification and the modulating effect of nutrient availability, through short-term CO_2 and nutrient enrichment experiments. I found elevated CO_2 enhanced larger phytoplankton growth and increased particulate C:N ratios under nutrient-replete conditions, but did not have a significant effect on size structure, growth, or stoichiometry under low nutrient conditions. In many tropical regions, coastal development and land use changes have resulted in increasingly nutrient-rich coastal seas, and our results suggest that in these conditions CO_2 enrichment may result in more efficient carbon flux to sediments due to the enhanced growth of larger phytoplankton and the production of more carbon rich particulate organic matter.

What new experiences did you gain?

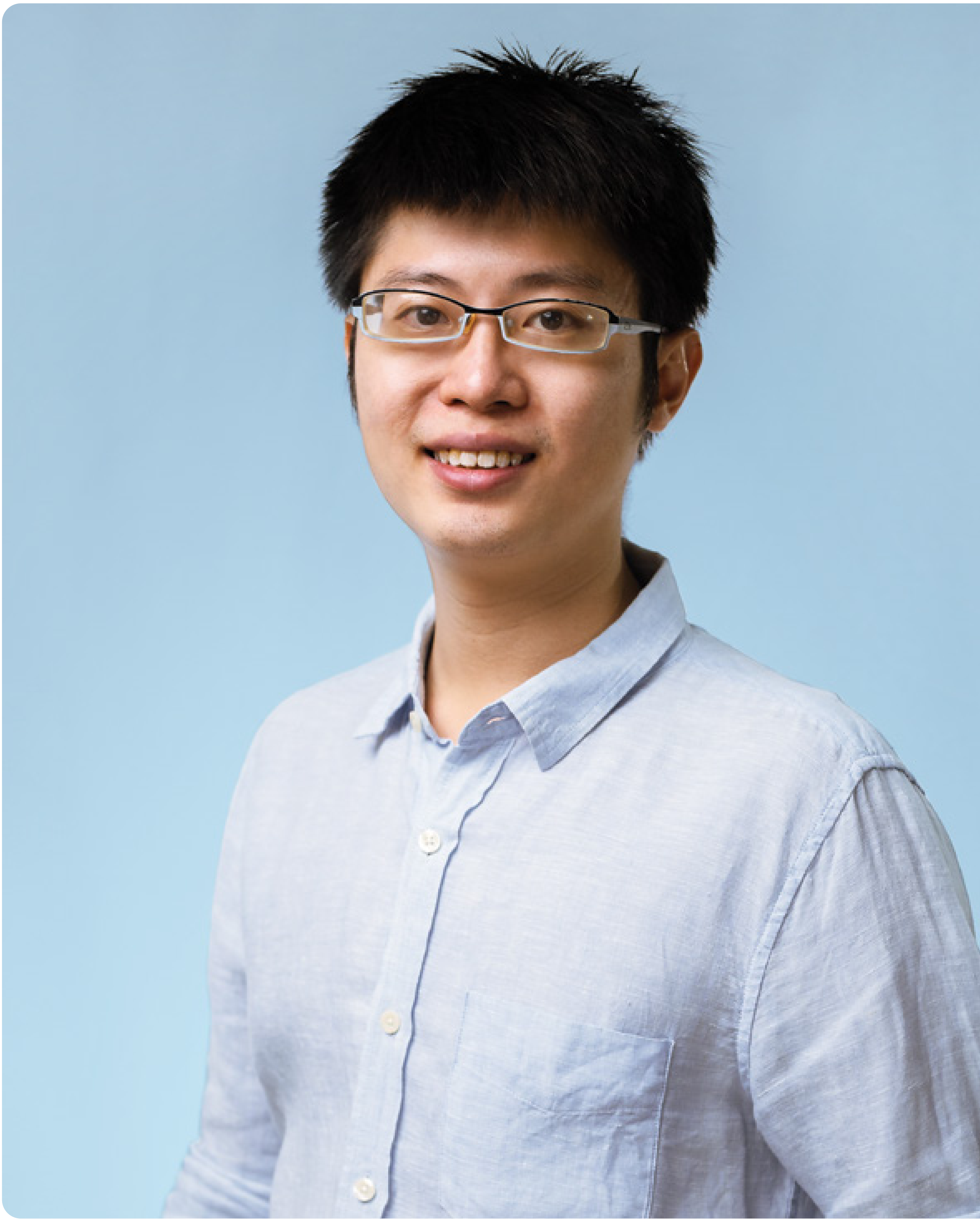
This PhD was full of new experiences for me, from learning how to run nutrient analysers, to creating coral fragment nurseries under the sea and running enzyme assay experiments on boats, to presenting at an international conference (before COVID-19), and, in my spare time, becoming a father and setting down permanent roots in Singapore with my wife.

What do you think are the key remaining questions in your field of marine science?

One key question is to determine the fate of dissolved organic matter from tropical peatlands out at sea. Does photo-degradation make it more labile to microbes and eventually it is remineralised to CO_2? Or does it dilute into the ocean and remain relatively stable in the ocean DOC reservoir over the long term?

What are one or two other key areas that should be prioritised for funding?

The research proposed in the above question are key areas that need to be prioritised for funding, as it is crucial to enhance our understanding of the cycling of the marine DOC pool, which is one of the earth's largest carbon reservoirs and is directly related to land use changes in Southeast Asia and the global climate.



Scholar

Aaron Teo

What was your PhD topic?

My PhD is on how sediment characteristics such as grain size and chemical composition can modify the negative effects of sediment on various stages of the coral life cycle.

What were the most interesting findings from your research?

The idea that coral larvae will not settle on surfaces composed of unconsolidated particles (e.g., sand) is not universally true once the particle size is large enough.

I gained valuable experience in handling coral gametes and larvae, which is often restricted by their annual occurrence and the manpower required to do so.

Also, coral reefs that are faring better in local waters appear to be receiving similar amounts of sediment as other reefs. The difference seems to do with how well the local current flow removes sediment.

What new experiences did you gain?

I gained valuable experience in handling coral gametes and larvae, which is often restricted by their annual occurrence and the manpower required to do so. Pre-COVID-19, I was able to conduct my fieldwork abroad so I could make comparisons with Singapore. I have been able to interact with a wide range of marine scientists and also mentor undergraduate students conducting their honours projects.

What do you think are the key remaining questions in your field of marine science?

There are too many to list. However, in regards to coral larval settlement, it is critical to identify the full list of factors that play a role in determining a suitable settlement surface.

What are one or two other key areas that should be prioritised for funding?

Annual sedimentation and algal growth patterns appear to be major factors influencing the health of local coral reefs, but this needs further research. Funding is also needed to identify the means to control or mitigate these factors as they will likely have a major effect on any attempt to restore or rehabilitate local reefs.

Scholar

Hannah Yeo

What was your PhD topic?

My PhD project is on trophic interactions on Singapore's seawalls, that is, on understanding feeding relationships between trophic levels from primary producers to first- and higher-order consumers on artificial coastal defences. Since coastal development increasingly threatens biotic interactions (e.g., competition, predation, herbivory, symbiosis, etc.) essential in ecosystem functioning, fundamental ecological knowledge on trophic interactions is required to inform effective conservation and management efforts.

What were the most interesting findings from your research?

From one of my experiments, I found that the absence of macroalgal growth at the higher shores on seawalls was not entirely due to harsh physical environmental conditions during low tides (e.g., high temperature, desiccation stress). When all macro-grazers (e.g., snails and fish) were excluded, macroalgae could grow at higher shore levels—providing evidence that grazers control the upper limits of algal distribution on seawalls. This finding is particularly useful for ecological engineering. For instance, materials that are more porous and with small indents in the surface may facilitate algal spore settlement that enables them to escape the rasping by grazing gastropods.

In addition, I documented photographic and video evidence of novel predator–prey interactions on Singapore's seawalls. These include unique video records of anchor tuskfish (*Choerodon anchorago*) crushing and eating nerites, which are one of the more common gastropods on seawalls.

What new experiences did you gain?

My PhD has honed my skills in critical thinking, project planning and management, experimental design, and other practical applications such as snorkelling and employing remote sensing for data collection (i.e., GoPro installations). My most notable experiences, however, involved designing, building, and constructing custom research apparatus that demanded creativity and systems thinking; all of which are invaluable skills that I gained over the past three years while setting up experiments.

My most notable experiences, however, involved designing, building, and constructing custom research apparatus that demanded creativity and systems thinking.

What do you think are the key remaining questions in your field of marine science?

As trophic interactions are generally less well-studied in urban marine systems, there still is a need to advance knowledge on this research frontier. We can move forward from investigating singular effects of climate variables on trophic interactions and start to explore how additive and multiplicative effects of multiple environmental variables shape trophic interactions on seawalls. Future work can also integrate experimental studies with climate predictions to understand how trophic interactions on seawalls are dynamically evolving in response to increased global warming and increasing urbanisation.

What are one or two other key areas that should be prioritised for funding?

There is a need for consistent, long-term research targeted at (1) understanding the fundamental ecology of urban marine systems, (2) applying this knowledge to design better ecological engineering solutions that can be applied at larger scales, and (3) research that elucidates the social aspect (e.g., motivations/limitations) of the public's perception and awareness on matters regarding conservation, education, and management of urban marine biodiversity in Singapore.

Scholar

Samuel Chan

What was your PhD topic?

My PhD looks at better understanding long-term changes in modern coral reefs. To do so, we look at them in context and compare them against past reefs. This is to ensure that we do not study modern reefs on a 'shifted baseline', in which successive generations look at reef changes across their own lifetimes, thus perceiving less change across all time as their baselines shift with each generation. With present-day reefs, we can simply observe them using various survey methods. However, for past reefs, we have to look through old photographs and records, and use cores extracted from the reefs, in combination with radiocarbon dating to understand how they change.

What were the most interesting findings from your research?

Singapore's reefs existed 7,000 years ago, with reefs also found at 6000 and 4000 years BP. While it is still unknown whether reefs persisted throughout these time points to modern day, the types of species found within the reef cores are similar to the species we find on reefs today, indicating that reefs may not have changed very much in terms of composition.

We have to prioritise resources into studies that can help build long-term data sets, which can then be used towards answering other, larger questions that span longer timeframes.

What new experiences did you gain?

Having to bridge multiple disciplines (ecology and geology), while using a new technique (reef coring), is always interesting because you can apply methods across disciplines to get closer to answers that may not be possible with just one discipline. I also received advice from different international collaborators that helped me understand some of the findings better and to put them into context.

What do you think are the key remaining questions in your field of marine science?

There are a large number of remaining questions on a variety of topics, especially in Southeast Asia. We have limited information on what reefs in the region were like in the past and how these compare to present-day reefs. We also need more studies on how the coral reef diversity in the region affects environmental changes in the reefs and how it will evolve with anthropogenic impacts.

What are one or two other key areas that should be prioritised for funding?

We have to prioritise resources into studies that can help build long-term data sets, which can then be used towards answering other, larger questions that span longer timeframes. We also need to look towards the study of ecosystem functioning, move away from single-metric-based ecosystem health assessments, and conduct more monitoring of environmental parameters.

Scholar

Si Kuan Thio

What was your PhD topic?

It was focused on smartphone-based portable microbial detection systems.

What were the most interesting findings from your research?

I discovered the potential possibility of performing in-situ and real-time monitoring of microbial water quality through portable loop-mediated isothermal amplification assays.

What new experiences did you gain?

I learnt about the importance of rapid detection of faecal contamination in environmental waters. I used conventional laboratory methods and portable methods of water quality detection (e.g., PCR, qPCR, LAMP, etc.) and had to learn DNA extraction (e.g., *E. coli*) from water samples. Through these experiences, I invented a portable smartphone-based microscopic system using a reversed lens concept, which was featured on the news and which I was interviewed for—it was an eye-opening experience.

What do you think are the key remaining questions in your field of marine science?

Key questions include pinpointing reliability issues of the portable detection system that I have been working on. Another issue would be about cross-contamination: conditions in the field are not as ideal as in the laboratory, so it is crucial to minimise contamination for this portable detection device.

What are one or two other key areas that should be prioritised for funding?

I was fortunate that MSRDP fully supported my work. Nevertheless, in the future, funding will still be needed to resolve the reliability and contamination issues mentioned earlier.

Scholar

Yong Jie Yip

What was your PhD topic?

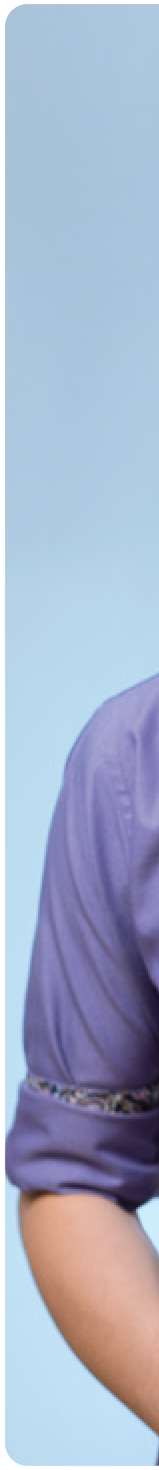
I investigated the effects of nanoplastics exposure, ingestion, and maternal transfer in marine animal models such as barnacles and tubeworms.

What were the most interesting findings from your research?

Plastics can break down into small particles, some smaller than bacteria. These may subsequently enter the food web of marine ecosystems, and be accumulated in all animals that ingest it, including humans. In my study, I found that these plastic particles may get passed on to the offspring of barnacles and tubeworms.

What new experiences did you gain?

Coming from a synthetic chemistry background, I had no experience in biological research and its expectations. This was an eye-opener: I learnt how even simple animals may eventually complicate simple experiments, so a great deal of independent problem-solving was needed.



This was an eye-opener: I learnt how even simple animals may eventually complicate simple experiments, so a great deal of independent problem-solving was needed.

What do you think are the key remaining questions in your field of marine science?

There is no consensus on the impact of our continued use of plastics on the environment. Even though the effects of nanoplastics on individual animal models have been reported widely, few have managed to answer sufficiently what the effects of plastics are on an ecosystem, or the environment as a whole. Endeavours can be focused on looking at ecosystem analogues, or to study a system as if it were one organism, instead of looking only at one animal model at a time, so as to get a bigger picture.

What are one or two other key areas that should be prioritised for funding?

My research focused on the effects of nanoplastics; it was a retrospective approach, rather than looking at what can be done to prevent the issue in the first place. While understanding the effects of our actions on the environment is important, an even more important endeavour is in understanding how to stop damaging the environment.

One key area to support is development of new materials to replace plastics, while being economically feasible. Sociological studies pertaining to public perception of plastic should also be prioritised for funding to help acceptance of constructive measures for protecting the environment and humanity from further harm.

EXPLORE: YOUNG MARINE SCIENTIST RESEARCH AWARD

Explore is a research-based capacity building programme for young students between 17 and 25 years old in undergraduate and pre-university levels who are keen on marine science. Through the research experience, Explore aimed to motivate students to develop technical skills and scientific literacy through active research interactions, moving from being passive learners to active scientists. The Explore programme funded a total of 44 student projects conducting exploratory research relevant to the four MSRDP domains at the St. John's Island National Marine Laboratory.

Explore Student

Sirius Ng

Tell us what motivated you to pursue research in marine science?

Marine megafauna has been one of my interests since I was young; however, I had been under the impression that these animals could not be found in Singapore. The lectures in university informed me otherwise—Singapore has several marine megafauna species; however, they remain understudied. At that moment, I knew that I wanted to find out more about these elusive animals. The Explore programme funded my Undergraduate Research Opportunities Programme in Science (UROPS) and final-year project, which focused on the dugongs found in our waters, providing me with the valuable opportunities to discover more about these animals. I am now enrolled as a PhD student at the Department of Biological Sciences, National University of Singapore.

What topic was your Explore project on?

My first Explore project focused on reconstructing the historical presence of dugongs in the waters surrounding Singapore and assessing contemporary feeding across several seagrass meadows. My second Explore project delved into the feeding ecology of dugongs in Singapore, in particular, diet, factors motivating food choice, and feeding site sustainability.

The very thought of conducting fieldwork on a semi-exposed reef in the middle of the Singapore Strait is just out of the world!

What new skills and knowledge did you learn?

Through both Explore projects, the biggest takeaways were time management and expenditure planning—both of which are important soft skills for researchers.

What was the most memorable experience you had during your Explore project?

I thoroughly enjoyed heading over to Cyrene Reef. The very thought of conducting fieldwork on a semi-exposed reef in the middle of the Singapore Strait is just out of the world!

Explore Student

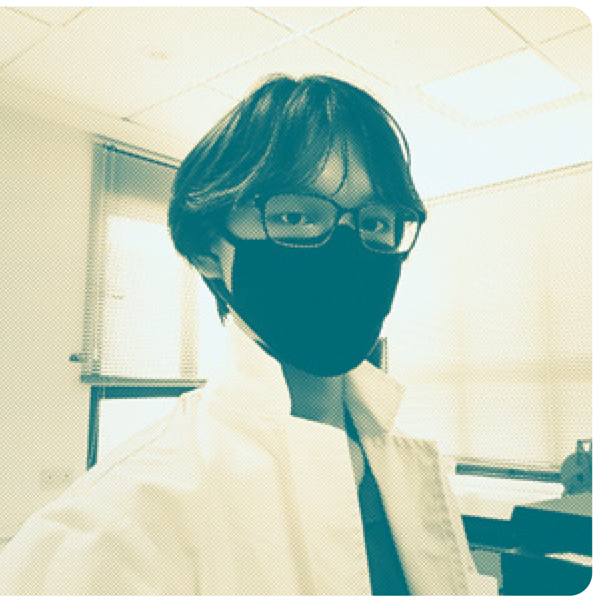
Mathias Luk

Tell us what motivated you to pursue research in marine science?

Since young, I have always been deeply fascinated with animals, marine life in particular. On family trips to the beach, I was usually found exploring the shoreline and tide pools. At that age, I knew I wanted to pursue marine science in the future. When the opportunity to participate in the Explore programme came up, I knew it was an experience too good to pass up, despite also having to study for Cambridge 'A' Levels at the time. I have since been accepted to the Bachelors of Environmental Science programme at the National University of Singapore.

What topic was your Explore project on?

My project was focused on studying and observing the effects of rising sea temperatures on a local sea anemone, *Isactinia citrina*, with an emphasis on investigating its bleaching and reproductive capacity; so little is known about its biology. I subjected these animals to a range of sea temperatures, simulating those predicted in the real world as global climate change persists. All this was done through a climate-controlled indoor aquaria at the St. John's Island National Marine Laboratory.



What new skills and knowledge did you learn?

Apart from biological knowledge, I also learnt to think critically on the spot. Coming from a relatively sheltered background of a junior college, I was so used to having larger figures ready with pre-prepared solutions to whatever problems I had, or a 'correct' answer to all my questions. I was caught off-guard once I started my project! If an aspect of the experiment did not go as planned or an unexpected problem cropped up, I had to learn to find a way to independently solve it. This exposed me to creative solutions. In this process, I also learnt how to overcome my anxieties and stress.

What was the most memorable experience you had during your Explore project?

It was by far the collection field trip. It was full of new experiences: from boarding the research boat at Sentosa Cove, to reaching the site only to find it deeply underwater, to walking along a seawall to reach another site. It was here that I first saw corals in the wild, a sight that thrilled me; I never expected to encounter them.

It was here that I first saw corals in the wild, a sight that thrilled me; I never expected to encounter them.

During the fieldwork, I had the chance to snorkel and explore the marine life in the wild—it was fun and interesting!

Explore Student

Sheena Heng

Tell us what motivated you to pursue research in marine science?

I am a fresh graduate from Temasek Polytechnic with a diploma in Veterinary Technology. In Year 3, we were given two streams to choose from: aquatic or veterinary. I chose the aquatic stream as I wanted to learn new things and gain new experiences in a different field. During a Year 2 veterinary course trip, I had the opportunity to go to Moreton Bay Research Station in Australia and work with the marine life there. This piqued my interest for marine science, so I chose the St. John's Island National Marine Laboratory as my preferred choice for an internship placement. Encouraged by my supervisors, I applied for the Explore grant.

What topic was your Explore project on?

My Explore project was on corals, specifically its susceptibility to bleaching during the 2020 coral bleaching event in Singapore. Coral bleaching around Singapore's reefs was observed in late May/early June 2020 when surface sea temperatures reached up to 32°C. In this study, I obtained data to show the impacts of the May/June 2020 heat stress event on the bleaching response (and recovery) of some corals commonly found in Singapore.

What new skills and knowledge did you learn?

I learnt many new skills, such as how to effectively conduct a literature review, and various laboratory techniques. Also, I had the opportunity to tag along during fieldwork trips to learn and help with coral sampling from the Sisters' Islands Marine Park and Kusu Island. I also learnt new aquarium skills such as fragmenting corals, using epoxy to attach them to building bricks, and computer skills such as using Image J to measure the surface area of corals. The literature review widened my knowledge of coral bleaching events that not only have occurred in our local waters, but also in the wider Southeast Asia region. All this helped me understand coral reefs better and appreciate the amount of work that goes into conducting research.

What was the most memorable experience you had during your Explore project?

It was going out to conduct fieldwork. I felt privileged to be given this chance especially given the COVID-19 restrictions that limited such learning opportunities. During the fieldwork, I had the chance to snorkel and explore the marine life in the wild—it was fun and interesting! I am thankful for the time spent with the other students at the marine station and my mentors and supervisors, who were patient with me and guided me in my Explore project.

OVERSEAS PROGRAMME AWARD

The MSRDP recognised the importance of undergraduates gaining experience in marine science at institutions outside Singapore and provided grants to Nanyang Technological University and the National University of Singapore to facilitate these key learning opportunities. Even though COVID-19 meant no students could leave Singapore in 2020 and 2021, the MSRDP was able to support a total of 38 student placements ranging from six to 16 weeks in locales around the world, including Sweden, Australia, Taiwan, UK, Thailand, Japan, USA, Ireland, New Zealand, Hong Kong, Finland, Cambodia, and the Netherlands.

Overseas Student

Jananee d/o Prakash Krishnan

I was fortunate to have the opportunity to embark on an overseas Undergraduate Research Opportunities Programme in Science (UROPS), especially so early into my university life (it was during the summer of my first year). I conducted my UROPS at the University of Plymouth in the UK, at the Marine Biology and Ecology Research Centre, funded by the MSRDP. While there, I assisted a PhD candidate with her research, conducting plankton identification and some data analysis.

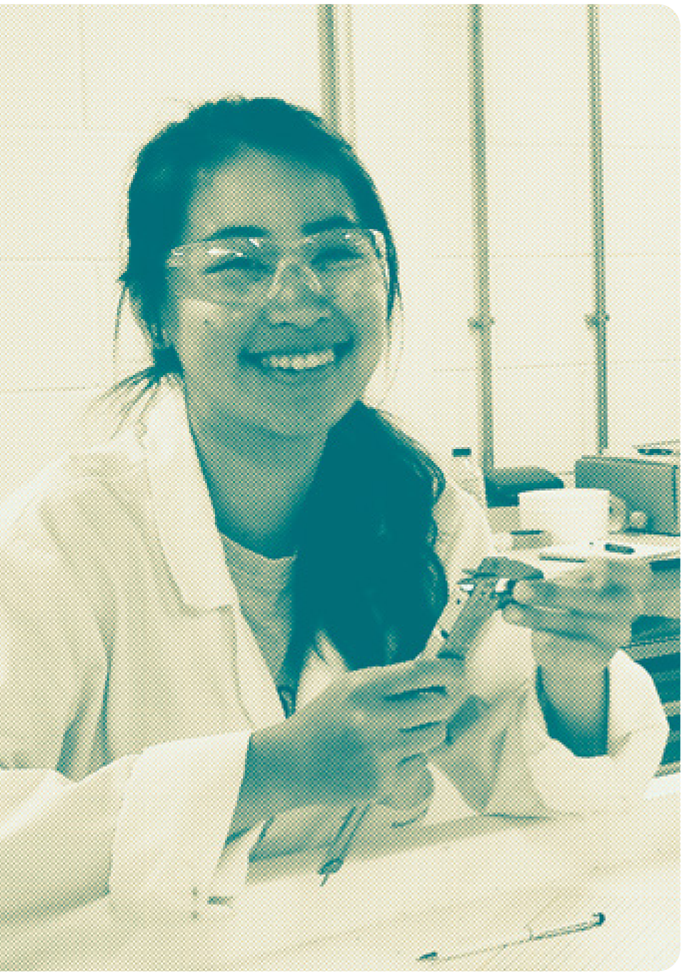
Apart from marine research, I was given an opportunity to attend two conferences: the Marine Biological Association Postgraduate Conference and the Plymouth University marine biology thesis presentation conference. For a university student still figuring out her interests, these events not only showed me the breadth of research in this field, but also filled me with excitement and joy, especially at seeing how passionate and invested these master's and PhD students were in their research topics.

Other than the academic aspect of this overseas experience, I gained the type of life skills that one can only get when pushed out of their comfort zone. Being alone, living and working in a foreign country at the age of 19 was a huge step for me, but the payoffs have been incredible, and I am so grateful to have been given the opportunity through the MSRDP programme.

Overseas Student

Clara Yong

In 2018, I had an MSRDP-funded opportunity to participate in an undergraduate overseas research programme at the University of Plymouth, UK. The research I was involved in aimed to increase marine biodiversity on subtidal seawalls through physical and biological enhancements. We hauled in tiles of different treatments that have been put out for 24 months, and measured the diversity and abundance of sessile organisms that had colonised them. During those months, I had an amazing time learning about the science behind the design of these tiles and the importance of physical complexity in a natural habitat. Not only did the research increase my awareness towards the magnitude of anthropogenic impacts, I was also inspired by the passionate scientists who were working hard to mitigate these impacts through applied science. I am grateful to have been given an opportunity to live abroad on my own, experience a different culture, and visit several coastal habitats outside Singapore. The project has now been completed and the results published in the journal *Frontiers in Marine Science*. Having been awe-inspired, I returned to Singapore and completed my honours research which aimed to help 'green' the seawalls through coral transplantation. I am now a year into my PhD hoping to understand the impact of microplastics on coral reefs, yet another anthropogenic-relevant project.



During those months, I had an amazing time learning about the science behind the design of these tiles and the importance of physical complexity in a natural habitat.

Overseas Student

Sirus Ng

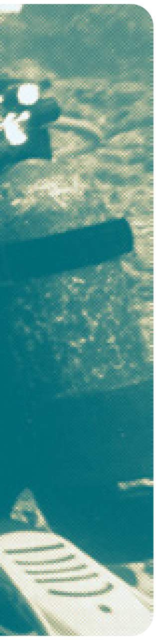
The MSRDP funded my student exchange to the University of Auckland (UoA) during my third year in the National University of Singapore. It was an eye-opening experience to take field courses at UoA's Institute of Marine Science and study in the ecological and nature reserves that the university had special access to. The naturalist in me revelled in being in natural spaces with endemic genera and species; all of which I have never seen before. Besides knowledge gained, this exchange programme introduced me to like-minded peers in the field of marine sciences. These are friends whom I still contact on a regular basis, and it is amazing that they were the ones who motivated me to step into the world of academia (I have just started my PhD)—even though we are thousands of miles apart.

It was an eye-opening experience to take field courses at UoA's Institute of Marine Science and study in the ecological and nature reserves that the university had special access to.

Overseas Student

Theodora Lee

The MSRDP played a significant role in helping me decide the career direction I wanted to pursue. I received relentless support and encouragement from my MSRDP supervisor, James Reimer, as well as other PhD and master's students from the Molecular Invertebrate Systematics and Ecology (MISE) laboratory at the University of the Ryukyus, in Okinawa, Japan, and I was inspired to become a researcher like them. Upon returning to Singapore, I immediately looked up opportunities to pursue a PhD in the environment sector. Amidst the countless challenges I have faced while planning and conducting my own research, I constantly reminisce about the feeling of sweet success after completing the research in Okinawa, and use those memories as motivation to continue my current work.



As a science student, I was able to witness how experts from other disciplines, from geography to marine biology and physics, combined their knowledge to further the field of oceanography, and to ultimately tackle climate change.

Overseas Student

Ming Sheng Ng

With the support of the MSRDP, I embarked on an NUS Undergraduate Research Opportunity Programme in Science (UROPS) with the Plant Physiology Laboratory at Prince of Songkla University (PSU) in Thailand. Under the supervision of Pimchanok Buapet, I studied the physiology of seagrass and its performance under thermal stress with coexisting macroalgae. I was not only exposed and equipped with general scientific skills such as experimental design and statistical analysis, but also many aquarium-based and specialised physiology analysis skills.

I also had the opportunity to share scientific knowledge with the community through various outreach programmes. We disseminated complex scientific ideas, climate problems, and potential mitigation options to people of all ages. I also got to discuss these issues with multiple stakeholders involved in climate change solutions in Thailand.

Throughout my time in PSU, I was able to meet professors and experts from various fields in the Coastal Oceanography and Climate Change Research Center (COCC). As a science student, I was able to witness how experts from other disciplines, from geography to marine biology and physics, combined their knowledge to further the field of oceanography, and to ultimately tackle climate change.

Overseas Student

Denise Ong

The MSRDP funded my 10-week research trip at the Tvärminne Zoological Station in Helsinki during the summer break of 2018. I assisted a team that specialises in the benthic ecology of the Baltic Sea, working closely with a PhD student at the time, Charlotte Angove, and her supervisor, Camilla Gustafsson. In my time there, my main task was processing the seagrass samples from an experiment on how the functional diversity of different seagrass communities affected the overall growth. I also assisted other researchers when they needed a hand in the field, and even learnt to drive a boat! On the weekends, I took trips out to different towns and cities of Finland to experience the local culture.

Throughout my 10 weeks there, I was definitely out of my comfort zone. The zoological station was in an area far from a town, and I had to ask someone to drive me once a week to get my groceries. I was the only Asian, and the youngest and least-experienced person in the station. However, my time interacting with the people there gave me a fresh perspective on those who work in science. I met people who were passionate about conservation; I met people who were accomplished in academia. It made me appreciate how science was for everyone, and a curious nature was what was most important.

That trip had certainly impacted what I do now: to continue in academia. I am now a PhD student in Nanyang Technological University, where I learn to use genomic methods to study plankton communities in the open ocean. The trip pushed me to later approach my final-year project and PhD with a curious mindset, resilience, and self-belief!

Overseas Student

Nikita Choudhary

The MSRDP programme funded my Undergraduate Research Opportunities Programme in Science (UROPS) to Okinawa, Japan, to conduct coral research. The Molecular Invertebrate Systematics and Ecology (MISE) laboratory under James Reimer was a welcoming and fun lab. I assisted various graduate projects with field and lab work: this involved activities such as free-diving to collect sea urchins and molecular analyses of soft coral samples. I was assigned a mentor who guided me through the scientific process of their research. This was an important learning process that I still relate to as I continue to work in research. I am glad that this opportunity allowed me to experience marine life in a geographical locality known for its coral diversity. More than anything, I cherish the relationships that I have built with fellow marine biologists worldwide.

I am glad that this opportunity allowed me to experience marine life in a geographical locality known for its coral diversity.

This project was my first-ever exposure to academia and allowed me to gain valuable insights into planning and executing experiments.

Overseas Student

Inez Alsagoff

The MSRDP provided my first overseas exposure into the world of marine research and the opportunity to work with a team of like-minded individuals. I was involved in a project based south of Stockholm, Sweden, on an island called Askö for two months in the summer of 2018.

This project involved lots of fieldwork and lab analysis. Fieldwork included taking a boat out to a nearby bay to set up fish traps and collect invertebrates and algae, while the lab work was mostly sorting and measuring the fish and invertebrates.

We also set up a large-scale mesocosm experiment (involving 80 mesocosms)—the most labour-intensive project that I have been a part of. The amount of manual work in setting up the entire structure prepared me well for other fieldwork-based projects I have since worked on.

The team consisted of seven female marine biologists from seven countries, all of whom were at different stages of their careers, from master's to PhD to post-docs. This project was my first-ever exposure to academia and allowed me to gain valuable insights into planning and executing experiments. Their enthusiasm and willingness to share their experiences and knowledge continue to remind me why I chose to pursue a career in marine science.

Overseas Student

Vanessa Quek

In June–July 2018, the MSRDP provided me the opportunity to travel to Hiroshima, Japan, under the Undergraduate Research Opportunities Programme in Science (UROPS). Under the supervision of Kazuhiko Koike and two master's students, I assisted with a study on giant clams and co-authored the subsequent paper.

In addition to my UROPS work, I was involved in other students' research that included soil sampling at mudflats, water sampling at oyster farms, and snorkelling fieldwork in Okinawa. Being involved in these various projects allowed me to have a better awareness of the range of marine environmental research and how impactful these studies are to understanding and protecting the planet we live in. I enjoyed this UROPS so much that I decided to do a final-year project as well. However, through all these experiences, I realised that I was keen to communicate research to the layman and translate research to real-life application. This led me to pursue a job relating to environmental consulting, which is what I am currently doing.

Through all these experiences, I realised that I was keen to communicate research to the layman and translate research to real-life application.

Overseas Student

Clarence WH Sim

I was awarded the MSRDP Overseas Award to participate in research attachments at the University of Queensland, Australia (2018), and University of the Ryukyus, Japan (2019). Both overseas research attachments fuelled my passion for marine research, so much so that I decided to pursue a PhD right after graduating from the National University of Singapore. I am currently in my second year of my PhD studying the geonomics and ecology of marine plankton (in the Arctic and equatorial waters) at Nanyang Technological University. I will always be grateful for the MSRDP for enabling me to gain such valuable experiences, such as meeting researchers from diverse backgrounds and exposing me to real science. It has led to where I am today, with lots of exciting opportunities.

I will always be grateful for the MSRDP for enabling me to gain such valuable experiences, such as meeting researchers from diverse backgrounds and exposing me to real science.

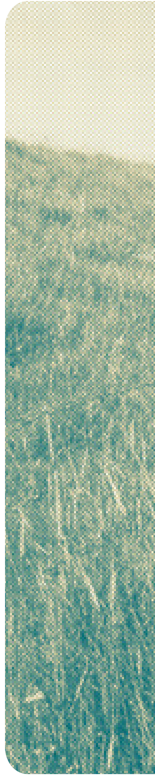
I am also thankful to the Australian and Japanese research labs that treated me with patience and kindness, and for the memories that I now hold dear to my heart. I can confidently say that the MSRDP was the catalyst to my passion and pursuit of marine research.

I had a memorable and enjoyable time as I got to experience life as a scientific researcher overseas in a completely new environment.

Overseas Student

Lewis JQ Low

Support from the MSRDP allowed me to embark on a six-week trip to the Prince of Songkla University, located in Hat Yai, Thailand. In the Plant Physiology Lab, led by Pimchanok Buapet, I met several students who were doing their master's and PhDs. This team helped me understand more about seagrasses and their various photoprotective mechanisms, which was the topic I was working on for my project with the Undergraduate Research Opportunities Programme in Science (UROPS). The laboratory experimentation skills and techniques that I gained were also relevant to many other modules in my studies at the National University of Singapore. All in all, I had a memorable and enjoyable time as I got to experience life as a scientific researcher overseas in a completely new environment. Personally, this experience had helped me mature and further solidified my interest in the field of marine science.



Overseas Student

Celine CY Chua

The MSRDP enabled me to study sediment signatures of coral reef islands near Perth, Australia, and it was one of the most valuable and memorable experiences of my undergraduate studies. Not only was it my first taste of hand-on research, it was also the first time that I had lived alone overseas away from my family for an extended period of three months. The work involved diving for coral sediments, as well as sediment identification and sorting. My supervisor at Curtin University, Nicola Browne, also gave me helpful tips as to how to better organise my report and write a scientific paper from scratch to present my results—advice that I still use to this day! I gained many research insights which triggered my interest and paved the direction of my future. I was inspired to take up another project with the Undergraduate Research Opportunities Programme in Science (UROPS) and have just started my final-year project at the National University of Singapore. But, most of all, I have become much more independent as I have learned to live independently in a shared house, to cook for myself, and to also interact with people from around the globe. It was a superb experience. Thank you, MSDRP, for granting me such an eye-opening opportunity!

Beyond work, I was also able to immerse myself in Dutch culture. The MSRDP provided me with one of the best experiences of my undergraduate career.

Overseas Student

Prasha Maithani

With support from the MSRDP, I undertook an overseas project under the NUS Undergraduate Research Opportunities Programme in Science (UROPS) at the Royal Netherlands Institute for Sea Research (NIOZ), examining the effects of sea-level rise on tidal flat sediment. My work there comprised both in-situ and flume experiments, with the in-situ component consisting of field and lab work. Our team would disturb experimental plots on the tidal flats to simulate increased hydrodynamic pressure, subsequently extracting sediment cores to analyse changes in the sediment profile. Some sediment cores were also used in the flume, a large hydraulic machine that used pistons to simulate wave action on the sediment surface.

This opportunity to study abroad was an invaluable experience. It served as an introduction to marine research and was highly influential in my choice to pursue an honours research project. I gained technical skills and was able to foster lasting relationships with my peers and supervisors at NIOZ. Beyond work, I was also able to immerse myself in Dutch culture. The MSRDP provided me with one of the best experiences of my undergraduate career.

A close-up of a sea anemone (*Alicia* sp.)

PROJECT SUMMARIES

A nudibranch, *Phyllodesmium macphersonae*, with finger-like projections extending from its body

Project Summaries

MARINE ECOSYSTEMS AND BIODIVERSITY (MEB)

P03

ADAPTATION AND RESILIENCE OF CORAL REEFS TO ENVIRONMENTAL CHANGE IN SINGAPORE

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[3] *Nanyang Technological University*

Introduction

Coral reefs constitute some of the richest and yet most threatened ecosystems on Earth. In particular, the Central Indo-Pacific marine realm that encompasses Singapore is home to the highest diversity of reef species in the world. Despite a small original reef area of 39.85km^2 recorded in 1953, prior to which little human impact is known, 255 species of reef-building corals and over 200 species of fish have been documented at Singapore's southern islands. Since the early 1960s, numerous reef habitats have been lost to land reclamation for urban uses, including petrochemical industries and port facilities. The remaining reefs still experience relentless chronic stressors, including sediment damage due to land reclamation and seabed dredging that have led to cumulative losses of more than 60% of the original reef area and up to 37% of coral species.

Figure 1: A coral reef in Singapore. *Credit: Danwei Huang*

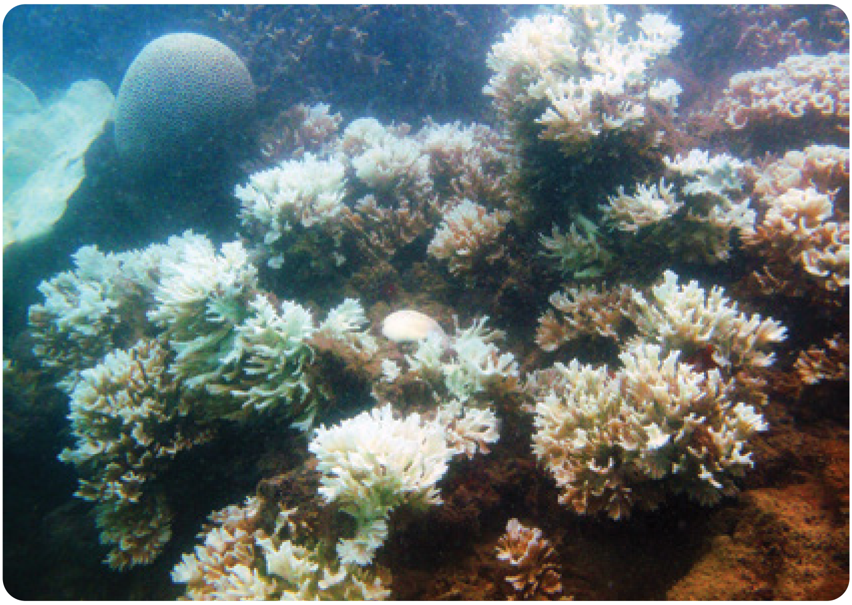

Figure 2: Coral bleaching in Singapore due to heat stress. *Credit: Danwei Huang*

The prevailing paradigm for coral reefs dictates that such chronic impacts would shift coral-dominated reefs to degraded rubble covered with seaweeds, but reefs in Singapore continue to support diverse and resilient coral communities. To understand how these species-rich habitats continue to endure, our project integrated historical and modern-day approaches to study reef adaptation and resilience.

Our project had two core objectives. The first was to reconstruct the genealogical and environmental history of Singapore's reefs over the last few millennia. We examined the structural and community profile of past reefs to determine changes in fauna over time and how these relate to environmental changes such as ocean warming and increased seaweed abundances. Complementary to this, we determined the ecological and evolutionary histories and genetic connectivity of reef-building coral populations. Our second objective was to investigate contemporary responses of reef corals and their associated microbiomes to heat and sediment stresses, as well as competition with seaweeds.

By extending the historical record of how corals have responded to environmental change, and by explicitly testing alternative hypotheses on how corals and their symbionts have responded to environmental stressors in the past and present, we have started to unravel how Singapore's reefs have managed to persist in one of the most urbanised marine environments in the world.

Main findings

Genealogical and environmental history of coral reefs

Reef corals anywhere on Earth have evolved over hundreds of millions of years, and nearly all species in this region originated prior to the establishment of modern coral reefs. Therefore, an in-depth understanding of the evolutionary and population histories of coral species is essential for assessing their abilities to adapt to Singapore's present and future environments. Our project developed novel approaches to characterise these histories, including the design of genome-wide markers for reconstructing the tree of life and population connectivity of corals, as well as the creation of new DNA sequencing and bioinformatics pipelines for discovering biodiversity.

The tools we developed enabled us to characterise the evolutionary history and diversity of numerous reef-associated groups, including microbes, seaweeds, sea anemones, corals, molluscs, echinoderms, as well as sharks and rays. In particular, for corals, we showed that coral populations are stratified from nearshore to offshore, and with differentiation of colonies at the farthest site from mainland Singapore. This information is important for management agencies when considering sites for biodiversity protection. For example, we found that Kusu Island is a major source of coral genetic variation, likely seeding many other Singapore reefs over several generations and thus should be accorded higher protection status.

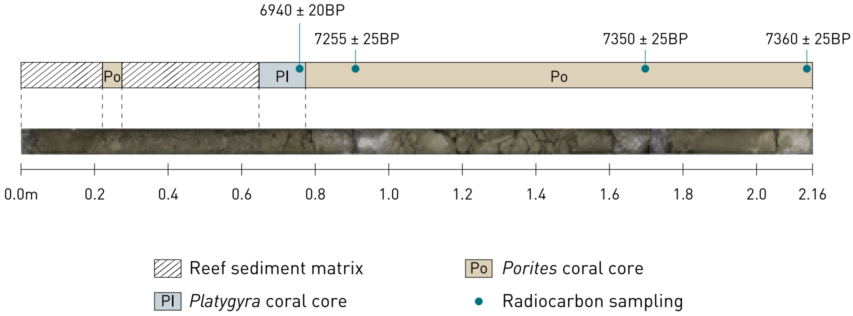

Figure 3: Core of reef showing radiocarbon age of a Singapore reef in years before present (BP). *Credit: Ambert Ang*

Coring and analysing deep into the past reefs in Singapore, we characterised the ages, identities, and abundances of calcifying organisms living in the past thousands of years. Results indicated that coral reef initiation began at least 7,400 years ago in turbid, low-energy depositional environments after the mid-Holocene sea-level rise. The reefs grew upwards to keep up with the sea level until a hiatus about 4,000 years ago, when reefs continued growing seaward. Interestingly, past coral community assemblages were generally similar to modern assemblages, except for the greater abundance of plating forms, which thrive in relatively low-light environments today. This suggests some light reduction occurred due to the build-up of suspended sediment, but otherwise comparable environmental conditions through millennia have driven reef dynamics.

Our analyses of coral cores also gave us a better picture of Singapore's reef environment in the last century. Using new methods to reconstruct nutrient availability on coral reefs by measuring the ratio of phosphorus to calcium in corals, we discovered multi-annual variabilities that seemed to be associated with the El Niño Southern Oscillation. Reconstructions using various other geochemical proxies also revealed disturbed nitrogen sources, sedimentation, and suspended particulates between 2000 and 2003 that coincided with a period of intensive land reclamation work to join Lazarus Island to Seringat and Kias Islands. Using coral skeletal luminescence, we were able to also reconstruct a 50-year record of seawater salinity for the Singapore Strait.

Figure 4: Core of massive *Porites* coral showing annual growth bands going back to 1940. *Credit: Jani TI Tanzil*

Ecological and microbial ecology of coral reefs

Reef corals live in symbiosis with multiple microbial organisms, principally the microalgal endosymbionts known as Symbiodiniaceae, as well as Bacteria, Archaea, Fungi, and viruses. These associations are modified or can break down during times of stress. For example, heat stress can drive the expulsion of the algal endosymbionts, resulting in coral bleaching. To investigate responses of the coral holobiont—comprising the coral host, Symbiodiniaceae, and microbiome—to contemporary stresses, we carried out the most comprehensive characterisations of these microbial components in Singapore's reef corals. Analyses showed that the Symbiodiniaceae communities are generally low in diversity, which could be a result of the strong selective pressure exerted by the prevalent turbidity.

Bacteria associated with corals and reef sediment were also examined, showing fine-scale spatial and temporal differences in bacterial composition. For example, corals at the lee and windward sides of the Southern Islands host distinct bacterial communities. A yearlong monitoring programme of two coral species on three reefs in Singapore also revealed a temporal shift in the microbiome with differences maintained between sites. A 10-day reciprocal transplantation study of corals between sites further demonstrated that coral microbiomes responded quickly to transplantation—even within a day—and remained dynamic throughout the experiment.

Reefs in Singapore have been impacted by sedimentation. Our surveys and experiments showed that coral-sediment contact is strongly influenced by coral morphology, with certain massive species and encrusting forms most likely to be covered by settled sediment. Higher sediment loads and finer sediment grain sizes also significantly reduce coral larval settlement rates. Studying both elevated temperature and sediment exposure with controlled experiments, we found that heat elicits much more extensive responses from both the coral host and endosymbionts, but a combination of these stressors can have synergistic effects on gene regulation in the coral holobiont. These gene expression changes are accompanied by photophysiological responses, including regulation of endosymbiont densities and synthesis of chlorophyll, a pigment to achieve optimal photosynthetic yield.

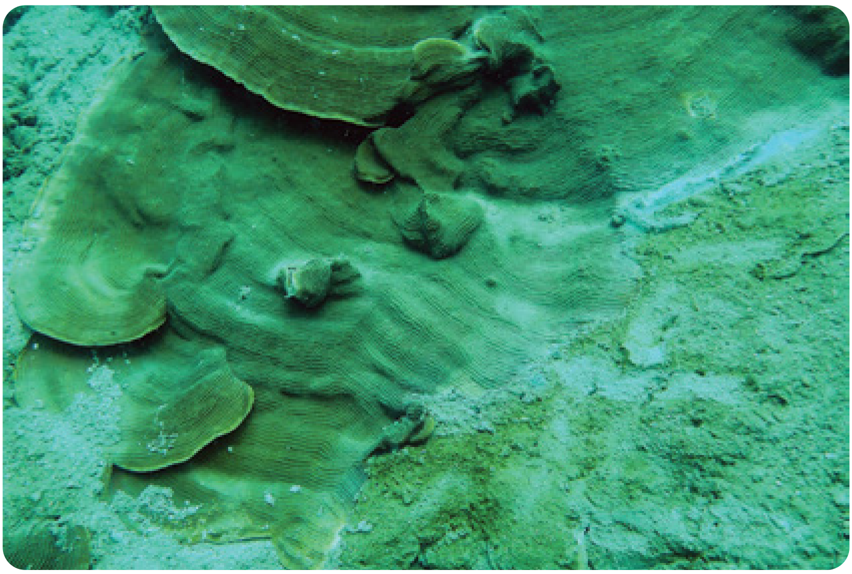

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Figure 5: Sediment encroaching live coral.
Credit: Danwei Huang

Competition between corals and seaweeds is also a major threat to the resilience of Singapore's reefs. Our extensive characterisation and experiments showed that the frequency of coral–seaweed interactions is variable across sites and seasons and that contact with seaweeds can reduce coral fecundity and even egg sizes. Increasing seaweed abundances can therefore constrain future reef recovery. The coral microbiome is also sensitive to both direct contact- and water-mediated interactions with seaweeds, while coral physiology is compromised only when in direct contact. Exposure of coral larvae to increasing concentrations of seaweed exudates generally leads to increased larval mortality and decreased larval settlement rates. Microbial response also varies with the concentration of algal exudate rather than the specific algal species.

When we tracked the herbivory-related seaweed dynamics over a year, there was marked variation in the removal of algal biomass. The highest removal rates occur between October and February, and the lowest removal rates are between March and August. We also examined how predator avoidance affects the foraging behaviour of seaweed browsers by simulating predator risk using fibreglass model predators (grouper *Plectropomus leopardus*). Browsing fishes take longer to begin foraging when in close proximity to the predator and consume considerably less seaweed at lower rates than browsers that feed at greater distances. Proximity to the predator also strongly influences the number of individuals foraging, with larger groups feeding more frequently on assays farthest away from the predator.

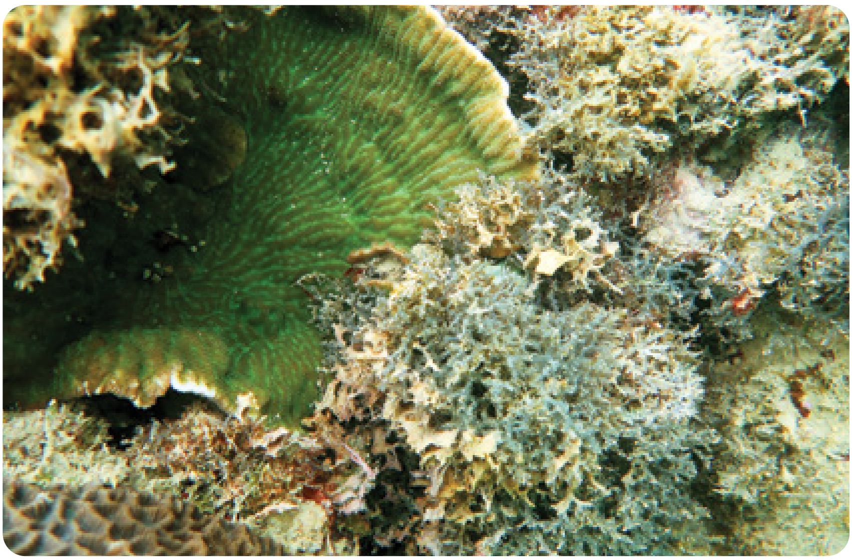

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Figure 6: Seaweed encroaching live coral. *Credit: Jenny Fong*

Accretion of coral reefs is the net result of gross carbonate production and erosional processes. To determine if the reefs in Singapore have the potential to accrete at sufficiently high rates to keep up with ongoing and future sea-level rise, we performed carbonate budget surveys across the reefs. Results showed that net carbonate budgets are low relative to other reefs in the Indo-Pacific, and a small minority of sites have a net negative, or erosional budget, due to near total loss of coral cover. Critically, their mean vertical accretion potential is below current rates and future predictions of sea-level rise, which will likely result in an increase of 0.2–0.6m of water above Singapore's reefs in the next 80 years, narrowing the depth range over which these reefs can persist.

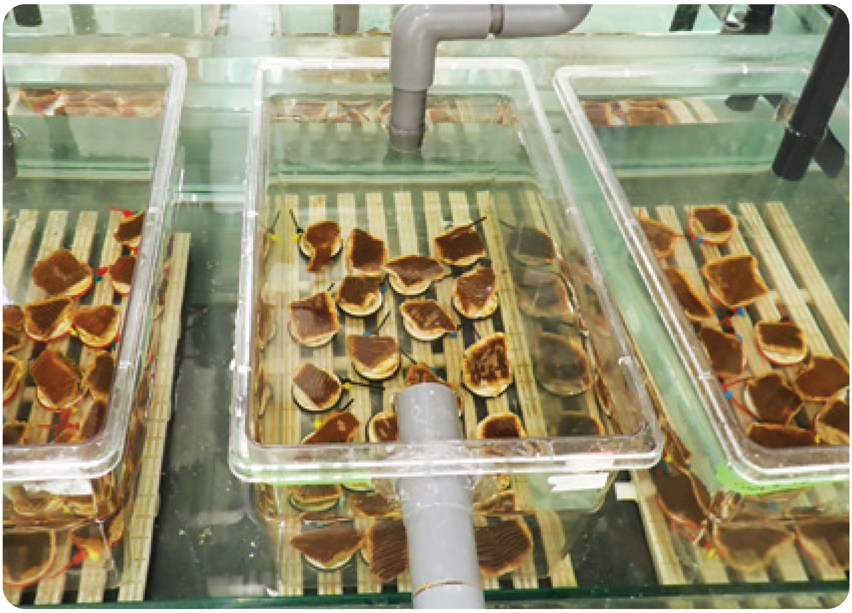

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Figure 7: Investigating the microbiome response to environmental stress at the St. John's Island National Marine Laboratory.
Credit: Lindsey Deignan

Future directions

Our project has started to build a picture of the genetic and ecological connectivity of organisms based on our work on corals, sea anemones, and symbiont communities including Symbiodiniaceae and bacteria. More organisms and microbial components need to be characterised for their distributions and genetic lineages to understand connectivity at various levels—from communities, species, and populations to microbiomes. This information is necessary for prioritising sites for habitat protection as they may be critically connected genetically and ecologically to affect recovery potential during times of stress, especially as the impacts of heat stress and sea-level rise are set to increase in intensity and frequency.

The project has been successful in characterising the effects of heat, sediment, and seaweed competition on corals, but much more needs to be known about the effects on other reef-associated organisms, including those that directly impact coral health such as seaweeds, herbivores, and bioeroders. Newer approaches in recent years have enabled the manipulation of host genes, endosymbiont communities, and microbiomes to raise the resilience of reef organisms and prepare reefs to be future ready. For example, we are conducting large-scale experiments at the St. John's Island National Marine Laboratory to investigate the effects of antibiotics on coral microbiomes and test if such treatments can enhance coral microbiome inoculation success. We hope to gain a better understanding of the microbiome response to environmental stress and develop better coral models for further experimentation.

Overall, we have contributed thousands of years of environmental reconstruction and reef growth data. We have also added an unprecedented amount of genetic information on the organisms, symbiotic algae, and microbes inhabiting Singapore's persistent coral reefs. These findings have been published in more than 80 international peer-reviewed papers. Most importantly, our project has developed the utility of the coral holobiont as a biomonitor of environmental change and provided probable trajectories of corals in the region. With more work in this area, we can truly begin to establish an early-warning system that provides rapid and precise projections of future reef conditions.

P07

TROPICAL MODEL MARINE ORGANISMS FOR EXPERIMENTAL MARINE SCIENCE

Serena LM Teo (PI)[1,2], Mei-Lin Neo (Co-I)[1,2], Suresh Valiyaveettil (Co-I)[3]

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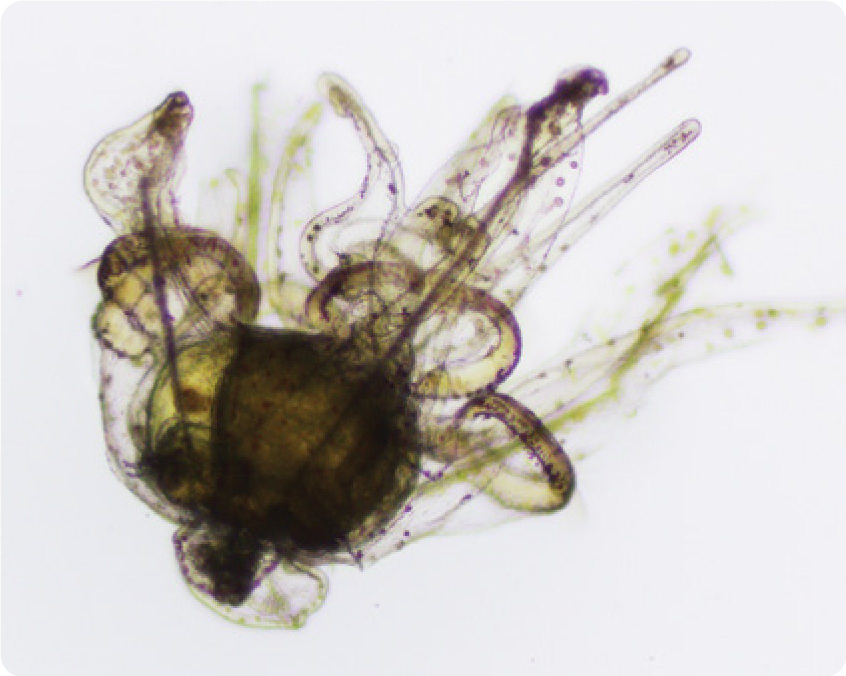
Introduction

Experimental marine biology research in Singapore is limited by the availability of living organisms for research. In the tropics, while biodiversity is high, abundance of individual species is low. In Singapore's busy waterways, with so few habitats within a small sea space, every field collection of animals for research poses a threat to the natural populations. The goal of this study was to establish laboratory cultures of tropical Indo-Pacific marine invertebrates to support experimental biology research. The study aimed to develop culture methods for three native marine organisms and establish a steady supply of organisms for research at the St. John's Island National Marine Laboratory.

As a demonstration of how experimental research using these native marine organisms contributes to advancing the science and monitoring of the marine environmental health, we conducted studies examining the effect of nano-sized plastics on their life cycles. The effects of fluorescent polymer nanoparticles in the size range of 100 and 180nm were prepared and exposed to two of the model organisms, *Spirobranchus* cf. *kraussii* (calcareous tubeworm with external fertilisation) and *Amphibalanus amphitrite* (acorn barnacle). The study investigated the ingestion, retention, and translocation of polymer nanoparticles in different life stages of these model organisms.

Main findings

The native white sea urchin, *Salmacis sphaeroides*, is now available at SJINML for research use. Techniques for its larval and adult culture have been established and made available to researchers interested to use this animal for their research. Sea urchins make excellent models for developmental and evolutionary biology studies due to their phylogenetic position at the base of the deuterosome lineage. Their simple and rapid embryonic development, and gene functions can be easily manipulated for testing hypotheses. Sea urchin embryos also grow well in artificial seawater, making them suitable for both laboratory and classroom use, and are amenable to many experimental approaches.



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Larval stages of the sea urchin, *Salmacis sphaeroides*.

Tubeworm gametes may be easily extracted for use in ecotoxicology studies, while larval stages are often used for testing the antifouling properties of marine coatings. Techniques for handling of the local tubeworm, *Spirobranchus* cf. *kraussi*, have been developed to support environment research.

Ascidians are the most primitive chordates and important model organisms in developmental biology. The larva has small numbers of cells, a very compact genome with genes similar to those found in vertebrates and occurring in single copy. This allows for genetic manipulation with effects observed within a short period. Techniques for handling of gametes and embryos of the ascidians, *Phallusia nigra* and *P. philippinensis*, are now in placed to support research in cellular biology.

The demonstration study showed that marine organisms may ingest and accumulate nanoplastics from the water column. These particles may be retained in the organism's body for a long time. Some plastics, such as polyvinyl chloride (PVC), are toxic to marine animals. Others, such as polymethyl methacrylate (PMMA), have little or no effect, but such polymers may absorb contaminants from the water column and facilitate the transfer of contaminants when ingested by an organism. These sequestered particles also affect reproduction and reduce the ecological health of the organisms. The study found that the extent of transfer of nanoplastics between parent and offspring differed among the model organisms. These results indicate that more research is needed to discern the environmental impacts of different plastics and enable better prioritisation in the management of ocean plastic pollution.

Future directions

This study paves the way for more basic experimental research using native marine organisms. More studies on the environmental impact of nanoplastics are underway, to enable the development of better strategies to manage plastic pollution.

P11

PHYSICAL AND BIOGEOCHEMICAL EFFECTS OF SEDIMENT TRANSPORT ON CORAL REEFS

Patrick Martin (PI)[1], Adam Switzer (Co-I)[1], Federico Lauro (Co-I)[1]

[1] *Nanyang Technological University*

Introduction

Corals are complex organisms: they obtain much of their energy from symbiotic algae, but these animals also harbour a large and diverse community of microbes. Because corals usually grow in relatively nutrient-poor waters, rapid nutrient recycling within the reef ecosystem is likely critical to their survival. Much of this nutrient cycling is driven by microbes, and it is thought that corals may rely especially on nitrogen-fixing microbes as a source of nutrition. However, most research on coral-associated nutrient cycling has been carried out under aquarium conditions, partly with contradictory conclusions. In this project, we took advantage of the large seasonal changes in nutrient concentrations in the Singapore Strait to quantify coral-associated nitrogen fixation and phosphorus cycling under real field conditions. We combined this with a detailed analysis of suspended sediment properties and sedimentation rates across our study sites.

Main findings

The Singapore Strait receives a seasonal nutrient input during the southwest monsoon season (May to September), with dissolved inorganic nitrogen concentrations exceeding typical eutrophication thresholds for coral reefs. In contrast, during the northeast and inter-monsoon periods, dissolved nutrients are often in the low nanomolar range, characteristic of very oligotrophic conditions.

Despite the large variation in dissolved nutrient concentrations, we found that the rate of coral-associated nitrogen fixation was relatively low and did not vary strongly with season. Much of the newly fixed nitrogen was actually assimilated by the microbes living in the coral skeleton (the so-called endolithic community), and not by the coral polyp or the symbiotic algae. Across different coral species and sites, we found that nitrogen fixation was carried out by a diverse but variable community of microbes with different niche requirements. This means that although microbial nitrogen fixation may be beneficial for the coral animal and its symbionts, it is unlikely to play an integral functional role in coral nutrition the way that the coral–algal symbiosis does. Our results also showed clearly that nitrogen fixation rates are not strongly dependent on ambient nutrient availability, which means that nitrogen fixation continues to add an input of new nitrogen to reefs even when nutrient concentrations are already elevated.

In contrast to the relatively low nitrogen fixation rates, we found that corals contribute to phosphorus cycling by expressing high levels of the enzyme alkaline phosphatase. We found that there is already high phosphorus cycling activity from the seawater microbial community, but that coral-associated alkaline phosphatase activity can contribute as much phosphorus cycling activity as in several metres of overlying water column. This year-round high rate of phosphorus cycling activity may be an important reason coral reefs are usually in a nitrogen-limited state despite the presence of a diverse community of nitrogen-fixing microbes.

Suspended particles show little seasonality and consist largely of silt-sized siliciclastic sediments. They are not a major part of the reef nutrient budget, but may affect coral health. Tidal currents are critical for maintaining particles in suspension, such that the net sediment accumulation rate on reef crests is very low (<0.2 mg cm^{-2} d^{-1}). However, the slower current speeds found deeper on the reef slope allow much greater net sediment accumulation of up to 1.2 mg cm^{-2} d^{-1} and this likely constrains the depth of coral growth in Singapore.

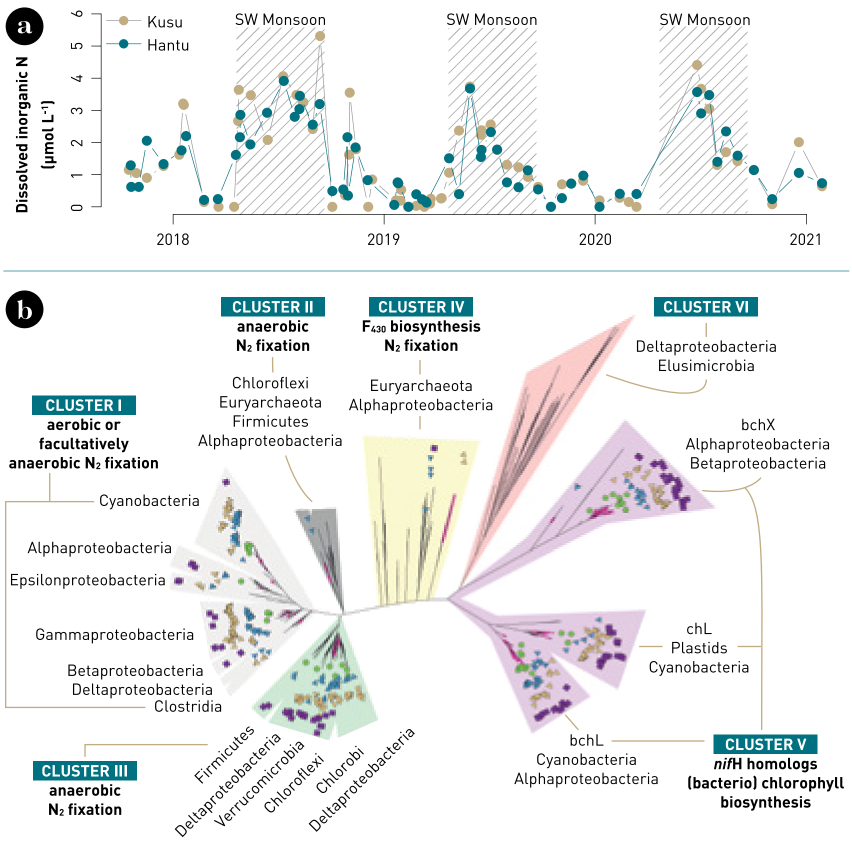

Figure 1: (a) The Singapore Strait receives large nutrient inputs during the southwest monsoon season (brown shading), shown here for dissolved inorganic nitrogen. (b) Phylogenetic tree of nitrogen-fixing microbes associated with three coral species at Kusu and Hantu reefs, based on *nif*H gene sequencing. Figure 1b is from Moynihan et al. (2021) *The ISME Journal*.

Future directions

Our results not only provide new insights into fundamental aspects of nutrient cycling on coral reefs, but also underscore the value of studying such processes in an environment with strong and predictable seasonal variation in seawater chemistry, such as Singapore. Important avenues for further work would be to understand the interplay between nutrient limitation and light limitation for benthic and planktonic communities in the Singapore Strait, especially in light of plans to expand aquaculture around the Southern Islands.

P13

UNDERSTANDING THE VIRAL COMPOSITION OF PHYTOPLANKTON BLOOMS IN SINGAPORE COASTAL WATERS

Federico Lauro (PI)[1], Sek Man Wong (Co-I)[2], Chee Yew Leong (Co-I)[2], Scott Rice (Co-I)[1]

[1] *Nanyang Technological University*
[2] *National University of Singapore*

Introduction

Viruses are the most abundant biological entities in the oceans, and can impact the composition of phytoplankton by reducing the abundance of selected taxa. Previous studies have shown that viruses can cause the collapse of large phytoplankton blooms, and some research has now started to examine whether viruses could be used as a biological control agent, to artificially terminate harmful algal blooms (HABs) in coastal waters. Viral control is particularly important for HABs because they are generally not subject to heavy grazing pressure by zooplankton, owing to chemical and mechanical defence. This project attempted to uncover the basis of the relationship between viruses and their planktonic hosts in Singapore's coastal water, where HABs have been impacting aquaculture, by performing an integrated analysis of viral and microbial assemblages in a time series over a duration of more than two years.

Main findings

The project has generated both technical and ecological insights. On the technical side, a rapid and accurate identification method for phytoplankton species was developed using third-generation sequencing technology. The Oxford Nanopore's MinION sequencer was used to sequence the entire 18S rRNA gene and part of the 28S rRNA gene of local phytoplankton species. While a major drawback of the Nanopore sequencing technology is its high error rate, we overcame this limitation by developing a custom bioinformatics pipeline that uses sequence redundancy to compensate for these errors. This approach has subsequently been validated by comparing the MinION sequences to precisely annotated sequences generated from either Sanger or Illumina sequencers. This method can now be extrapolated to rapidly and precisely characterise phytoplankton blooms in Singapore—an event that recurs on an annual basis—to serve as an early warning sign to fish farmers, enabling them to better protect their livestock. The long-read sequences generated with this method have also been used to create a publicly available Long Amplicon Sequence Repository (LASeR): laser.ase.ntu.edu.sg/home.

Ecologically, this project has established the first long-term observatory for viriome (the collective biome of viral communities) in Singapore's coastal waters. This was achieved by collecting monthly samples of phytoplankton and viruses at

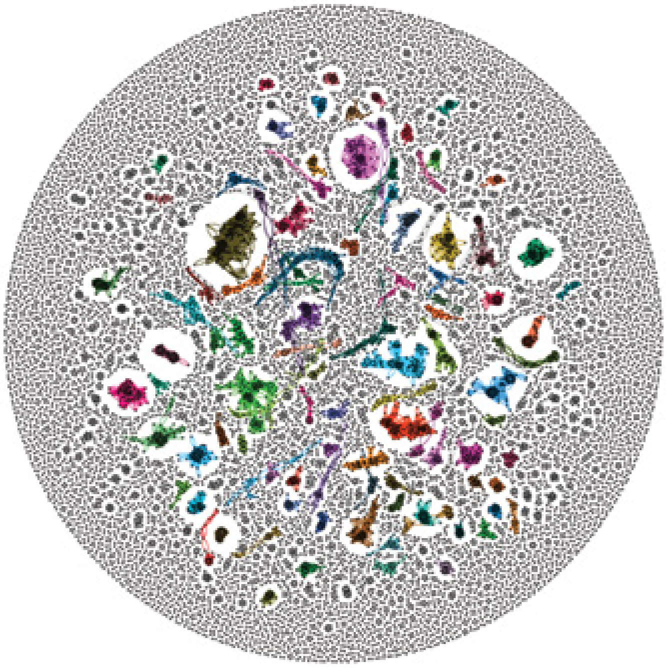

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Figure 1: A bird's-eye view of the viriome of Singapore's waters. Each dot represents an individual genome and lines connecting them indicate a high degree of genome similarity. While most genomes are unique in the data set, some are reoccurring both in time and space: the largest clusters of genomic sequences have been highlighted in colour. *Courtesy of Enzo Acerbi*

five stations across Singapore's local waters, together with associated oceanographic parameters (i.e., temperature, salinity, nutrients, DOM/POM).

The viral community in each sample was characterised using a hybrid approach with two sequencing technologies (i.e., Illumina and Nanopore). Thousands of almost complete viral genomes could be retrieved from Singapore's coastal waters (Figure 1). An analysis of these genomes suggests that viruses use different life strategies in response to variations in the availability of nutrients and hosts present. In addition to observing a unique viral composition reflecting the difference in trophic status between those encountered in the Straits of Johor and Singapore, our research revealed a seasonal variability of viral communities in the Singapore Strait, which was mainly influenced by the monsoon systems.

Future directions

The funding for MSRDP-P13 has provided an opportunity to develop new approaches in metagenomic sequence analyses and also, the capacity to acquire time-series data of microbiome and viriome samples at five locations around Singapore. A key outcome of this project has been the recovery, from the metagenomic data, of thousands of almost complete viral genomes. Our results also suggest that viruses in Singapore's waters use different life strategies in response to variations in nutrient and host availability, which has broad implications for the control of specific microbial populations, and potentially the establishment and demise of harmful algal blooms. Furthermore, by analysing the communities of the microbial hosts as a function of differences in trophic status between both straits, this research uncovered a seasonal variability of the plankton communities that is influenced by the monsoon systems. This highlights important dynamic links between marine plankton and their viruses within the coastal waters of Singapore, generating a baseline and reference for all future plankton–virus research in the tropics.

The biggest opportunity arising from this project has been the capacity to expand the scope into understanding RNA viruses. We have successfully started developing a revolutionary solid-phase PCR method, which provides quantitative insight into the absolute abundances of important RNA viral types in response to changes in environmental conditions.

P18

CODEFISH-SG:

Building a foundation for a unified marine biodiversity knowledge base by analysing Singapore's marine ichthyofauna using morphological and molecular tools

Henning Seedorf (PI)[1], Zeehan Jaafar (Co-I)[2], Gen Hua Yue (Co-I)[1]

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[2] Department of Biological Sciences, National University of Singapore

Introduction

Biodiversity surveys are essential for assessing the health of ecosystems and providing information for management decisions. This is especially relevant for the marine habitats in Singapore, an area considered the world's busiest transhipment hub, that are particularly vulnerable to anthropogenic degradation of marine environment. Benthic organisms, such as the hard corals, have been the emphasis of much of the local research in the past few decades. However, fishes are an excellent focal group when carrying out marine biodiversity surveys as they are ubiquitous and abundant, and have been traditionally used as proxy organisms in biodiversity assessments.

Comprehensive inventories documenting marine fishes from Singapore have never been attempted, and only few surveys exist for specific fish taxa. The lack of DNA barcoding for most local fish specimens and incomplete digitisation of the museum collection make it difficult to gauge marine or local/regional representations. Archiving DNA barcodes and maintaining the information in a barcode library allow for future reference of all fish fauna. This encompasses the differentiation of native and invasive species as well as the identification of fish larvae and molecular analyses of cryptic species. An established DNA barcode library will also be an important foundation for the environmental DNA-based analyses of the local marine ichthyofauna.

Main findings

More than 10,000 fish specimens were collected during an intensive survey period at the Singapore Marine Fish Expedition (SMFE) and 1,057 fish specimens through small-scale sampling sessions at 13 locations. The SMFE, a special workshop organised as part of this project, was held at the laboratory facilities at the Lee Kong Chian Natural History Museum (LKCNHM) from 1–12 August 2019. This expedition involved international and local experts, and was organised in collaboration with various entities within NUS (LKCNHM, Department of Biological Sciences), Temasek Life Sciences Laboratory, National Parks Board, local volunteer groups (e.g., Naked Hermit Crabs), and interested stakeholders (e.g., Marine Stewards Singapore, Wild Singapore). Fish specimens were collected from 49 sampling sites using the different fishing techniques.

Overall, a total of 1,315 fish specimens were identified via morphology and genetic barcoding. These specimens belong to two classes, 27 orders, 97 families, 257 genus, and 500 species. All specimens were catalogued, preserved, and deposited in LKCNHM. Photographs and tissue samples were extracted from 611 specimens. At least one specimen per species was barcoded for this project. In total we generated DNA barcodes of both cytochrome oxidase 1 gene and the 12S rRNA gene for more than 300 species with at least two or more specimen and another >150 barcodes for species where only one specimen was available.

We also performed barcode-based and morphological analysis of *Pseudogobius javanicus*, a potential cryptic species complex. Two clusters of sequences were consistently observed in the pairwise similarity analysis for both COI and 12S rRNA genes (Figure 1). One clade consisted of one specimen from Sungai Loyang and two specimens from Coney Island. The other clade comprised six specimens collected from Sungei Buloh Wetland Reserve in 2012 and 2017. More specimens are being analysed to better understand the genetic and morphological variations in this species complex, but these results already illustrate the potential of barcode-based analysis of cryptic species.

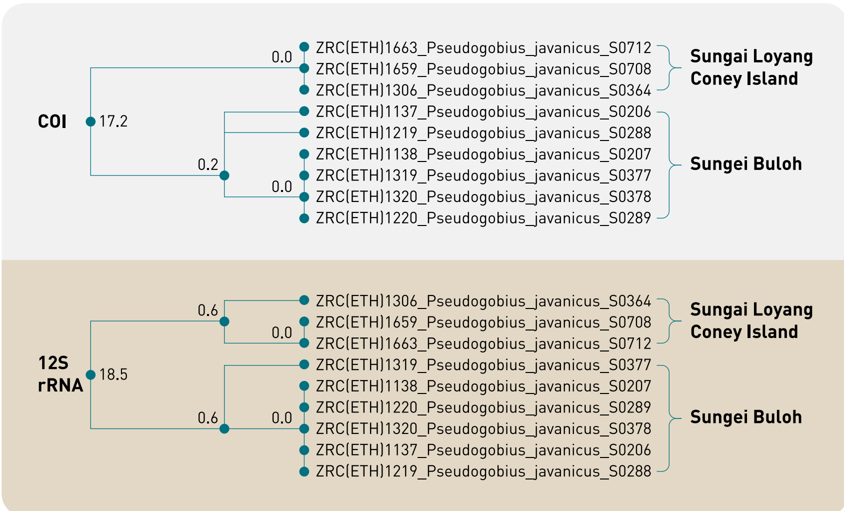

Figure 1: Cluster dendrogram from a pairwise similarity analysis of *Pseudogobius javanicus* sequences. Numbers at each node represent the percentage pairwise differences.

Using the DNA barcode library, we are able to establish an environmental DNA-based analysis of the marine fish diversity in Singapore. We collected water samples from 17 sites that encompass a wide range of marine habitats, and at two time points (during monsoon and between monsoon seasons) across Singapore. Environmental DNA was extracted from the water samples and metabarcoding was performed using primers designed to detect fish-specific 12S rRNA genes signals. Approximately 250 species of fish could be detected from these different water samples.

Future directions

The results from this project build a strong foundation for future analyses of the different facets of the marine ichthyofauna in Singapore. This can specifically include the regular monitoring of the ichthyofauna using a metabarcoding approach to determine the effects of climate change or invasive fish species on the local ecosystem. But the morphological and molecular analysis of the fish species can also be complemented by characterising the species-specific microbial communities that are associated with each fish species.

P19

POPULATION-GENOMIC AND HABITAT STUDY OF HORSESHOE CRABS OF SINGAPORE

Byrappa Venkatesh (PI)[1], Frank Rheindt (Co-I)[2], Laura Yap (Co-I)[3], Jasmin Lim (Co-I)[3], Yi Long Ng (Co-I)[3], Karenne Tun (Co-I)[4]

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[2] *National University of Singapore*
[3] *Republic Polytechnic*
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Introduction

Horseshoe crabs are one of the most iconic marine resources of Singapore. They are ancient creatures that have existed for approximately 500 million years but have changed very little over this long evolutionary period, earning them the moniker 'living fossils'. Horseshoe crabs play an important ecological role in the marine food chain as both predators and prey. For example, the nutrient-rich eggs of horseshoe crabs are an important diet of migratory shorebirds. In human medicine, the horseshoe crab blood lysate (known as limulus amebocyte lysate or LAL) has long been used for the detection of bacterial endotoxin contamination in injectable drugs and medical equipment. Despite their long evolutionary history, there are only four living species of horseshoe crabs worldwide. Singapore is home to two: the mangrove horseshoe crab, *Carcinoscorpius rotundicauda*, and the coastal horseshoe crab, *Tachypleus gigas*. The populations of these species are under threat due to coastal development, habitat loss, and irresponsible fishing (horseshoe crabs are often found entangled in fishing nets). There is a need to formulate strategies for managing the existing populations of horseshoe crabs in Singapore. However, no systematic study has been carried out to assess the population sizes and dispersal patterns of horseshoe crabs around the coast of Singapore. Among the two Singapore horseshoe crabs, the smaller mangrove horseshoe crab is listed as 'Vulnerable', whereas the larger coastal horseshoe crab is listed as 'Endangered' on the Singapore Red List. Our project's goal is to understand the distribution, genetic diversity, and population structure of both species of horseshoe crab in Singapore.

Main findings

A Survey and tagging

A population survey and habitat study showed a higher abundance of the mangrove horseshoe crab than the coastal horseshoe crab in northwestern Singapore. This is consistent with the occurrence of the largest proportion of mangrove forests on the main island at Sungei Buloh Wetland Reserve, Mandai, and Kranji. In contrast, the coastal horseshoe crabs were found in northeastern Singapore where there are more sandy beaches. A total of 37 horseshoe crabs were tagged with CART tags and/or GPS tags. The monitoring data showed that there was only limited movement of horseshoe crabs (180–730m) from their release points.

B Genomics

We generated high-quality, chromosome-level, whole-genome sequences and transcriptomes of the two species of horseshoe crab. Detailed analysis of the mangrove horseshoe crab genome revealed that the population of this species experienced a sharp decline approximately 60,000 years ago coinciding with the onset of the last Ice Age. The population never recovered from that decline. An unexpected finding was that the horseshoe crab lineage experienced three rounds of whole-genome duplication (WGD). WGD is usually associated with species radiation and diversity. However, horseshoe crabs are represented by only four living species, raising questions about the relationship between WGD and species radiation. Another interesting finding was that several genes involved in innate immunity were found to have undergone tandem duplications giving rise to a large number of immune system genes. This expansion of immune gene repertoire may explain the highly sensitive immune system of the horseshoe crab whose blood is used for testing bacterial endotoxin contamination in drugs and medical equipment. Many of the expanded gene families code for antimicrobial peptides and hence are potential candidates for developing novel antimicrobial compounds.

C Population genomics

We collected DNA samples from 304 individuals of the two species around Singapore and across the complex archipelagic Singapore Strait. Analysis of tens of thousands of genome-wide genetic markers showed that the less mobile mangrove horseshoe crab has undergone continuous Holocene decline in genetic diversity, whereas the dispersive deep-water coastal horseshoe crab remained stable until about 3,000 years ago and then steeply declined in diversity, probably in response to a spike in regional mangrove formation. The mangrove horseshoe crab is considered more vulnerable to the loss of genetic diversity because of disconnection among habitats, especially with the Singapore Strait potentially posing as a barrier. Therefore, we would suggest that the mangrove horseshoe crab receive a high conservation priority. Preservation and restoration of mangrove habitats around the Southern Islands are also essential to conserve regional genetic diversity of the mangrove horseshoe crab. Creation of sandy beach sanctuaries along the northwestern coast of Singapore will provide protected breeding grounds for coastal horseshoe crabs and ensure their continued breeding in Singapore.

Future directions

The data generated in this study will help the government in policy planning, to achieve recovery of declining horseshoe crab populations through legislative governance, restoration of mangrove habitats, and beach restorations as done in the United States and Hong Kong.

We have taken a lead in the population-genomic and conservation studies of horseshoe crabs in Southeast Asia and have established ourselves as experts in this field using our genomics and population genetic knowledge. We hope to apply similar techniques and strategies for studying other marine resources of Singapore and the neighbouring regions.

P22

MOLECULAR BIOLOGY OF INORGANIC CARBON ABSORPTION, TRANSPORT AND ASSIMILATION IN THE FLUTED GIANT CLAM, *TRIDACNA SQUAMOSA*

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Introduction

The fluted giant clam, *Tridacna squamosa*, inhabits the shallow tropical waters of the Indo-Pacific coral reefs. Tropical waters are low in nutrients, but giant clams can attain high growth rates and conduct light-enhanced shell formation because they live in symbiosis with dinoflagellates (also called zooxanthellae). The symbiotic dinoflagellates reside extracellularly inside tertiary tubules located mainly in the extensible, fleshy, and colourful outer mantle. During insolation, the photosynthesising symbionts share with the host photosynthates that can satisfy about 100% of the host's energy requirements. To support photosynthesis, the host needs to supply the symbionts with inorganic carbon (C_i), which is also needed for light-enhanced shell formation involving the whitish inner mantle. Hence, the host clam must absorb exogenous C_i through its ctenidia, which have a large surface area for gas exchange and ion transport. The objectives of this project were to elucidate the mechanisms involved in three processes in *T. squamosa*. These include (1) the absorption of exogenous C_i through the ctenidium into the hemolymph, (2) the translocation of C_i from the hemolymph into the luminal fluid of the tubular system where the symbionts reside, and (3) the translocation of C_i from the hemolymph into the extrapallial fluid where light-enhanced calcification occurs.

Main findings

A The absorption of C_i from the external seawater through the ctenidium

The complete cDNA sequence of Dual-Domain Carbonic Anhydrase (DDCA), which comprises two distinct α-CA domains, has been cloned from the ctenidium of *T. squamosa*. DDCA has an apical localisation in the epithelial cells that form the tertiary water channels and those that cover the base of the ctenidial filament. During illumination, the transcript and protein levels of *DDCA*/DDCA are upregulated in the ctenidium, denoting its involvement in the light-enhanced uptake and assimilation of exogenous C_i. To facilitate C_i uptake, more H^+ is needed for the increased dehydration of HCO_3^- to CO_2 in the ambient seawater during illumination. Indeed, the ctenidium of *T. squamosa* expresses Vacuolar-type H^+-ATPase (VHA), and the protein abundance of VHA subunit A (ATP6V1A) increases significantly (~2-fold) after exposure to light as compared with the control. VHA is positioned to excrete H^+ to the external medium because ATP6V1A has an apical localisation in the epithelial cells of the ctenidial filaments and tertiary water channels. Hence, the ctenidium of *T. squamosa* can increase the excretion of H^+ through VHA to augment the dehydration of exogenous HCO_3^- during light exposure.

B The delivery of C_i to symbionts in the colourful outer mantle

To facilitate the supply of C_i to its symbionts, the irridocytes and the epithelial cells of the zooxanthellae tubules in the outer mantle of *T. squamosa* possess a light-dependent carbon-concentrating mechanism (CCM). The CCM consists of a homolog of Carbonic Anydrase 2 (CA2-like) and VHA. Iridocytes are strongly ATP6V1A-immunopositive, indicating the expression of high levels of VHA. Hence, they can probably increase the secretion of H^+ to the hemolymph to augment the dehydration of HCO_3^- to CO_2 during illumination. CO_2 can permeate the basolateral membrane of the tubular epithelial cells into the cytoplasm, which expresses a homolog of CA2 (CA2-like). As the protein abundance of CA2-like increases significantly in the outer mantle of clams exposed to light, CA2-like can be part of the mechanism to increase the supply of C_i to the photosynthesising zooxanthellae by the host clam.

C The translocation of C_i into the extrapallial fluid to support light-enhanced calcification

The inner mantle of *Tridacna squamosa*, which is involved in shell formation, has a light-dependent mechanism of exogenous C_i absorption. This mechanism consists of an apical Carbonic Anhydrase 4 homolog (CA4-like) and a cytoplasmic CA2-like in the seawater-facing epithelium of the inner mantle, which also possesses an apical β-Na^+/H^+ exchanger to promote the dehydration of HCO_3^- in the external medium.

Future directions

Coral reefs are currently threatened by climate change, coastal pollution, and various anthropogenic activities. Symbiotic reef animals can undergo a stress response called 'bleaching', which leads to the loss of symbiotic dinoflagellates. Notably, giant clams can act as reservoirs of symbiotic dinoflagellates in the reef ecosystem because they harbour large quantities of symbionts. They can expel healthy and viable dinoflagellates that can repopulate bleached dinoflagellate-bearing hosts including scleractinian corals. Hence, future studies should examine the effects of bleaching and recovering from bleaching on the molecular mechanisms of C_i transport and assimilation in giant clams. Information obtained may provide insights into novel ways to protect giant clams from the negative impacts of climate change, which may in turn help to protect the coral reef ecosystems.

P25

BIODIVERSITY OF MARINE MUSSELS IN SOUTHEAST ASIA

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Introduction

As a major international maritime hub, Singapore has its share of non-native marine and estuarine species. In early 2016, an infestation of a hitherto unrecorded true mussel was observed along the estuarine shores of the Johor Strait. Identification of mussels to species remains notoriously difficult and often frustrating in Southeast Asia. Species diversity is high, with many looking very much alike and possessing overlapping taxonomic characters that greatly hamper species identification. Their taxonomy is often further confounded by the uncritical use of multiple scientific names. For these reasons, there is now much confusion in the literature regarding their species identities, particularly for common mussel species found in Southeast Asia. The project aimed to clarify taxonomic uncertainties surrounding common mussel species in the region by using a combination of morphological and molecular techniques to define each species. Another key objective was to differentiate native from non-indigenous mussel species.

Main findings

The project examined species belonging to the mussel genera *Brachidontes*, *Xenostrobus*, and *Arcuatula* (also previously known as *Musculista*). We ascertained that the mat-forming mussel *Brachidontes striatulus* (Figure 1a), which was earlier thought to be a non-native species in Singapore originating from India, is not affiliated to the genus *Brachidontes*. This was based on evidence from molecular sequences of three nuclear and two mitochondrial genes. We found that the species is genetically distinct and a new genus *Byssogerdius* was proposed to accommodate it. Based on these findings, we suggest that Indian specimens of *striatulus* are probably erroneously identified in the past and may actually be another, yet undetermined species. On the other hand, *Byssogerdius striatulus* is a widely distributed species that occurs across Southeast Asia and tropical Australia.

At the same time, we also discovered a morphologically similar species, *Byssogerdius subsulcatus* (Figure 1b), that sometimes occur together with *B. striatulus*. Previous workers have generally assumed *Byssogerdius subsulcatus* to be the same species as the externally similar *Brachidontes setiger*. We have suggested that *subsulcatus* and *setiger* are probably quite unrelated, and the latter species should be placed in the genus *Gregariella* instead, which comprises species distributed mainly in the Mediterranean Sea and the west coast of Africa.

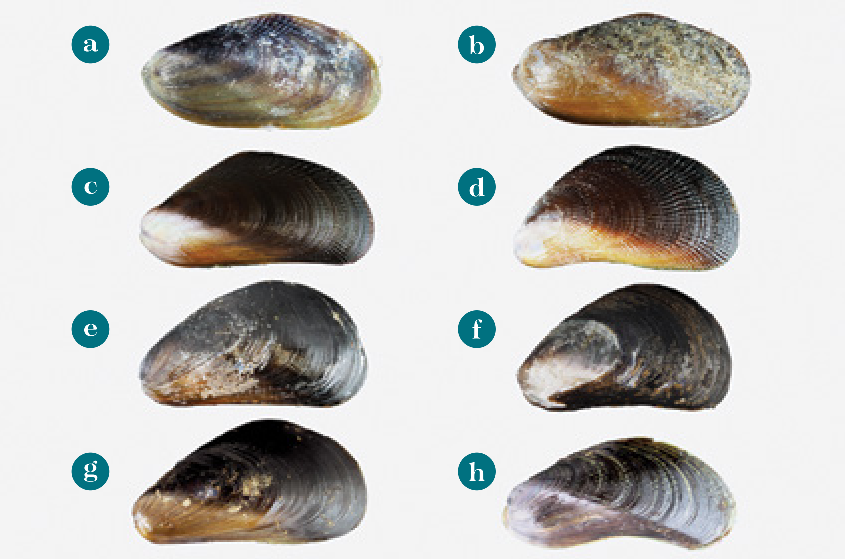

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Figure 1: A selection of mussel species from Singapore, Thailand, and Japan that were considered in the study. All shells shown are between 1cm and 2cm in size. (a) *Byssogerdius striatulus* from Singapore; (b) *Byssogerdius subsulcatus* from Singapore; (c) *Brachidontes variabilis* from Singapore; (d) *Brachidontes mutabilis* from Singapore; (e) *Xenostrobus mangle* (=*balani*) from Thailand; (f) *Xenostrobus atratus* from Japan; (g) *Xenostrobus* cf. *sambasensis* from Thailand; (h) *Arcuatula* cf. *cochinensis* from Thailand.

Another taxonomic quagmire that we attempted to resolve involves several other species in the genus *Brachidontes*: *crebristriatus*, *mutabilis*, *pharaonis*, *ustulatus*, and *variabilis* (see Figure 1c, d). They have a wide Indo-Pacific distribution, ranging from East Africa through the Middle East, South and East Asia to Australia and Hawaii. Their shells are nearly impossible to distinguish morphologically due to their inherently variable taxonomic characters. Based on genetic and anatomical analyses, our results so far suggest that there may just be two (or three) widely distributed, highly variable species in Southeast Asia. If this is true, there are significant implications for the management of marine invasive species in our region.

We also had some success in establishing the phylogenetic relationships between species of *Xenostrobus*, a genus of mussels comprising several common species distributed across Australasia and New Zealand. Based on our results, it seems likely that there are now three (instead of four) native species found in East Asia: one species (*mangle*; see Figure 1e) that is widespread across Southeast Asia, another (possibly new) species (Figure 1g) documented for the first time in Thailand, and one (*atratus*; Figure 1f) that occurs natively in northeast Asia. Another species, originally from Australia (*securis*), is now known to be alien and invasive in east and northeast Asia. Further analyses may prove that the Southeast Asian species together form a sister group to the Australian species.

Finally, our ongoing work on the taxonomy of *Arcuatula* suggests that there are probably two or three widespread species occurring in Singapore. However, it is unclear if one of them (*cochinensis*; Figure 1h) is an alien species originating from India, or whether its original distribution encompasses India and Southeast Asia. The synonymy of *A. senhousia* and *A. arcuatula* are also uncertain.

Future directions

Field collection and examination of museum material have been adversely affected by COVID-19 travel restrictions. We hope to continue our collaborative activities once travel restrictions are lifted so that the work on the Indo-Pacific species of *Brachidontes* can be brought to fruition. We also endeavour to resolve the phylogenetic relationships between *Arcuatula*, *Limnoperna*, and other poorly known estuarine/freshwater mytilids in Southeast Asia.

P41

THE IMPACT OF QUATERNARY CLIMATE CHANGE ON HORSESHOE CRAB POPULATIONS IN THE SUNDA SHELF

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Introduction

Quaternary climate oscillations have led to extensive cyclical sea level changes across the Sunda Shelf, impacting population structure and diversification of marine organisms in unknown ways. Despite detailed insights into the impact of sea level changes on terrestrial animals and freshwater fauna, limited research has been carried out on coastal marine species. Three of the four extant living fossil species of horseshoe crab across Southeast Asia provide us with a unique opportunity to examine evolutionary responses to sea level changes.

Main findings

We sampled hundreds of thousands of genomic single nucleotide polymorphisms from over 250 individuals of all three Asian horseshoe crab species, *Carcinoscorpius rotundicauda*, *Tachypleus gigas*, and *T. tridentatus*, covering their entire natural range. We discovered that *C. rotundicauda* has the most spatially structured populations, suggesting multiple refugia during glacial maxima. Moreover, low dispersal ability and rapid expansion across the shelf after the last glacial maximum may have led to the formation of highly localised populations of *C. rotundicauda* across Southeast Asia. It is likely that *T. gigas* retreated to the Indian Ocean during the last glacial maximum and recolonised the Sunda Shelf afterwards. *Tachypleus tridentatus*, whose distribution may not relate to the coastal dynamics of the Sunda Shelf, forms two clades, one based in Japan and the other based in Palawan and East Borneo. The populations in South China and Northern Vietnam may be the admixed descendants of both clades. Our findings suggest more substantial contributions from the Indian rather than Pacific Ocean during the formation of biodiversity of coastal habitats in the Sunda Shelf after the last glacial maximum.

Future directions

The three Asian horseshoe crab species provided us with an example of how coastal marine biodiversity may have shaped the Sunda Shelf after the last glacial maximum. However, given horseshoe crabs' unique biological features, for example, their long generation time of over ten years, it is worth exploring the evolutionary histories of other coastal marine species using this study's framework. This will provide a more comprehensive picture for the formation of marine biodiversity in Southeast Asia. For the horseshoe crabs specifically, and in light of their inherent ecological and biomedical value, it is worth exploring the evolutionary history of multiple important genes in adaptation and immunological functions using our sample collections from across Asia.

Horseshoe crab.

P44

FEASIBILITY STUDY FOR THE DEVELOPMENT OF A KNOWLEDGE ORGANISATION SYSTEM (KOS)

of marine environmental data for Southeast Asia (KOSMESEA) to support implementation of marine environmental law and policy

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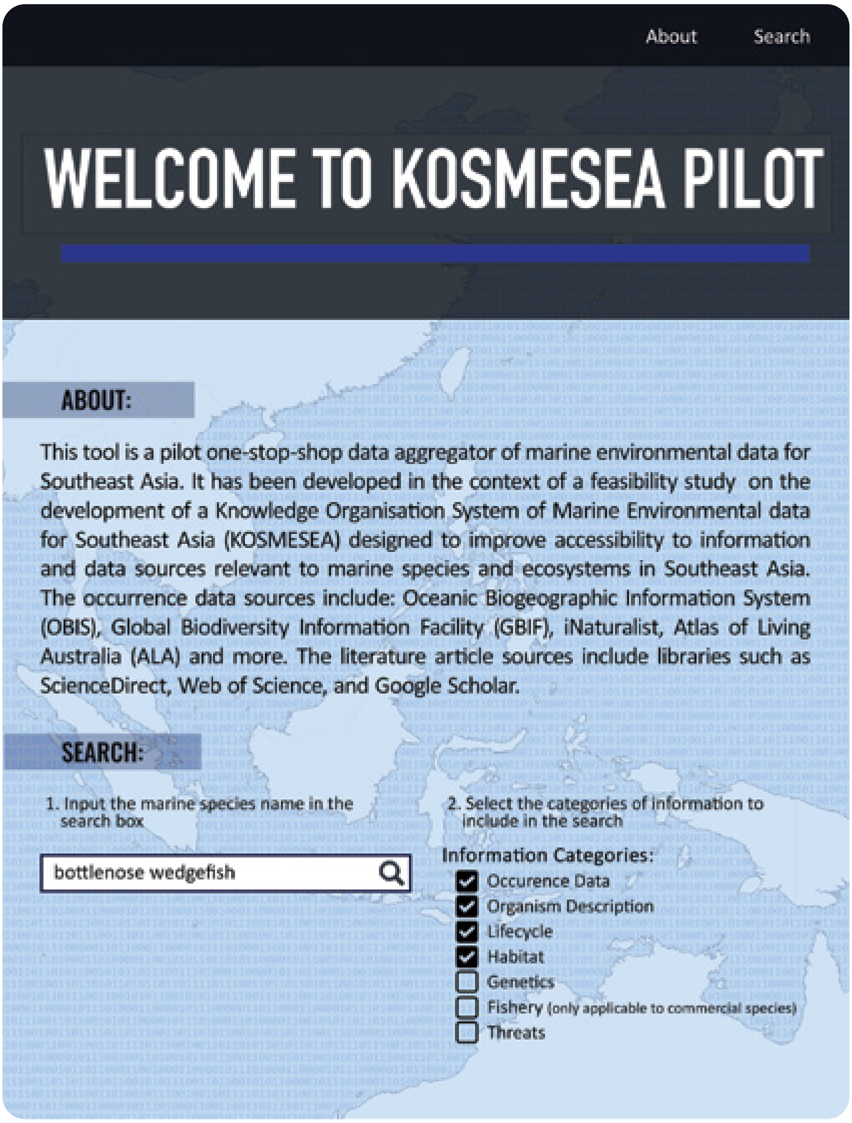
Introduction

Records of marine environmental data relating to Southeast Asia are scattered around the world in a number of private and institutional hands, in different formats (reports, journals, conference proceedings, digital, hard copies) as well as in global and regional databases developed for different purposes, systems, or taxa, and with different metadata. This results in gaps in knowledge for the management and protection of the marine environment in Southeast Asia and a handicap to policymaking at regional and global levels.

The main objective of this feasibility study was to understand the basis and possible configuration for a KOSMESEA to be developed. It involved a partnership with National University of Singapore library and a regional consultation. Findings were also shared with institutional data holders in Southeast Asia.

Main findings

- The hypothesis of the existence of non-digitised or difficult-to-access reports and records (often in hard copy) was confirmed.
- Awareness of this issue is rising, and there are a number of ongoing initiatives to overcome it as well as digitised records of old manuscripts and publications, but they appear to remain mostly scattered and so far, unsuccessful in substantially changing the situation.
- Preliminary metadata harmonisation proved successful.
- Experimental PDF text extraction is promising, highlighting the possibility of extracting data that is not captured by digital data repositories.
- Automation of text extraction is currently at a bottleneck due to the difficulty in implementation. We have consulted with various communities and discovered potential for collaborative work, which can yield possibly cutting-edge and competitive outcomes.



Future directions

- Making regional data from the 1980s and 1990s available for baseline determination.
- Developing direct data access paths between relevant public records in ASEAN institutions by leveraging existing efforts at university and national levels in ASEAN countries and with other data and knowledge holders.
- Developing text extraction of marine environmental data. There are other research teams outside the region trying to harmonise future data collection, but there is a lack of initiative on data collation and integration for presently available data within the region. There is therefore a perfect window of opportunity for Singapore to push its investment in data science through marine environmental data and further develop its leadership position whilst providing value for the region.

P47

GENOMIC ANALYSIS OF THE SEA SKATER *HALOBATES*

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National University of Singapore

Introduction

There are an estimated 5.5 million insect species living on earth, but only a tiny fraction of fewer than 5,000 species are found in the marine environment. The most notable marine insects are the sea skaters, belonging to the genus *Halobates*, which are one of the rare few genera of marine organisms capable of living on the sea-air interface. *Halobates* comprises 49 described species that can be found in coastal lagoons, intertidal reef areas, estuaries, and mangroves. It also includes five species which are the only insects found in the open ocean, and are noteworthy for being able to live their entire lives out on the ocean surface without the need to return to shore.

Despite their unique characteristics and relative widespread distribution, little is known about their evolution and genetic makeup—specifically how their distinctive traits originated and are coded in the genome. Genome sequencing data will enable the annotation and analysis of genes evolved over millions of years that are specialised for the insect's ocean-dwelling capability, and provide a clearer picture of how this enigmatic genus diversified in the oceans. The information will also provide insights into how animals are able to recolonise the oceans after being specialised for life on land.

The main objective of this study was to sequence the nuclear genome of the coastal marine insect *Halobates hayanus* in Singapore, along with mitochondrial genomes of close relatives, which will enable us to reconstruct the evolutionary history of the genus to infer gene evolution over time.

Main findings

We sequenced and analysed the mitochondrial genomes of specimens collected from Singapore and Papua New Guinea, comprising 15 specimens of *Halobates* (including *H. hayanus*), *Halovelia novoguinensis*, *Haloveloides papuensis*, and *Theribates serena*. All 15 mitogenomes assembled contain 37 genes (13 protein-coding genes, two rRNAs, and 22 tRNAs), and no change in gene order was observed.

Halobates insects are the only marine organism known to be able to live on the sea-air interface. In order to survive in the ever-changing and some of the harshest marine habitats, they have evolved many unique adaptations to cope with life on the ocean surface. Some of the most important adaptations of *Halobates* include the development of elaborate body hair layers that keep them from drowning when accidentally submerged by storms or wet by rain, and an ability to withstand overheating from solar radiation and to avoid UV damage to their reproductive organs.

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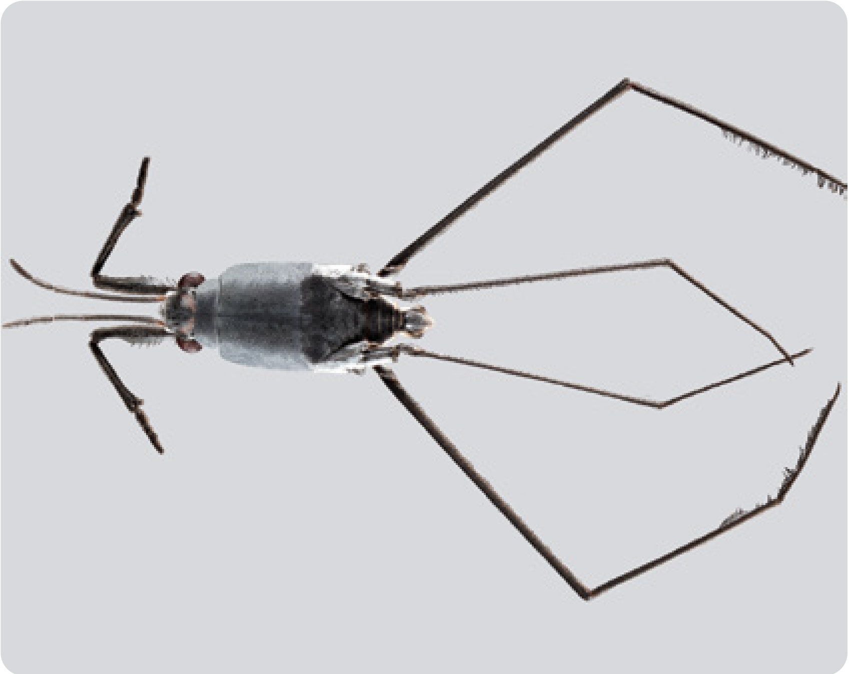
Figure 1: *Halobates hayanus*. *Credit: Marc Chang*



By characterising the unique genomic architecture of these insects, we can understand how *Halobates* has been able to evolve, diversify, and be successful in the marine environment. This is especially pertinent in this era of anthropogenic ecosystem degradation and climate change, and the findings provide us with fundamental knowledge to predict how such uniquely adapted species will fare in the warming oceans.

More specifically, we have contributed the first genomic data for marine insects, adding an unprecedented amount of genetic information on animals living on the sea-air interface. Our project has developed *Halobates* as a prime example of how new adaptations may arise, expanding our ability to forecast the wide variety of organismal responses in the marine environment.

Future directions

While the genome of *Halobates hayanus* was sequenced here, it needs to be assembled and annotated accurately to enable inferences about the specific genetic adaptations that allow these unique insects to survive in the sea, move about on the sea-air interface, and disperse itself to become one of the most widespread marine insects in the world.

Indeed, how this coastal species has managed to disperse across the vast oceans remains a mystery, given the need to remain close to shore to find food and solid egg-laying substrates. There is a need to estimate the population structure and gene flow patterns of *H. hayanus* in order to investigate its origin, species divergence, and population dispersal. Such an approach can be similarly employed to address other mysteries of *Halobates* that continue to elude researchers, such as the origin and diversification of the genus, as well as the process by which some species managed to return to the sea and even colonise the open oceans.

A sea star, *Ophidiaster granifer*, from Sister's Island Marine Park

Project Summaries

ENVIRONMENTAL IMPACT AND MONITORING (EIM)

P04

BIOTA EFFECTS ON THE ENVIRONMENT:

An impact source neglected in EIAs

Seng Keat Ooi (PI)[1], Nhan Phan-Thien (Co-I)[2] [replaced by Boo-Cheong Khoo (Co-I)[2]]

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Introduction

Biota (living organisms), when subjected to chronic environmental stress, produce adaptive responses to survive. These responses feed back into the physical environment, resulting either in a relief from the environmental stress or a perpetuation of the initial stressors. When the latter happens within coral reef ecosystems, they could degrade beyond a chance for natural recovery. Current models used for predictive environmental impact assessments (EIAs) do not take into account adaptive responses and ecosystem function, therefore feedback into the abiotic system is not considered. This results in the underestimation of effect sizes and overestimation of ecological thresholds, and ultimately leads to excessively permissible operational triggers.

Corals have to cope with high sediment loads in Singapore's waters and some of these responses, in turn, influence the soft-sediment dynamics in a coral reef environment. In this project, we focused on documented elevated organic matter production (i.e., mucus production) in corals in response to sediment stress, and the effects of increased organic matter on processes affecting the movement of fine sediments around coral reefs. We aimed to (1) improve systems understanding of how living corals and coral reefs in turbid environments affect the aggregation and binding of particulate sediments; (2) identify the resultant implications on sedimentation, transport, and sediment accretion processes; (3) translate the resulting knowledge for inclusion into models that support predictions and scenario analyses; and (4) develop reef-scale non-hydrostatic deterministic numerical models.

Main findings

The sediment binding potential of mucus greatly increases the retention of sediment particles in the coral reef ecosystem. Mucus in a coral reef ecosystem is produced by corals in response to a stressor, as well as by other reef organisms such as tubeworms as a feeding mechanism. Buoyant mucus are capable of trapping and keeping particles in suspension for a long time, particularly during low current velocity periods, e.g., during slack tides where there is little change in current velocity profiles. Over time, as more particles adhere to the mucus aggregates, they become heavy and sink to the seabed. This process, in turn, increases the amount of particles settling on the seabed and the accretion of sediments on the coral reef. Given the appropriate current velocity condition, seabed sediments that are bound by mucus aggregates are able to resuspend into the water column, resulting in a deterioration of water clarity.

To understand the mucus and its behaviour better, we developed a microstructure model for viscoelastic thixotropic fluids. This model is relatively simple and has only a small number of parameters, which makes it convenient for engineering simulations. The model was shown to produce reasonable results to clay suspensions in oscillatory flows.

In Singapore, due to the proximity to shipping channels, the shallow water coastal environments are not only influenced by natural effects, e.g., tidal currents and wind-generated waves, but are likely to be also significantly affected by turbulent water movement due to vessel passage. Fast ferries and large container vessels are capable of generating ship wakes that can rapidly stir up seabed sediments. Being able to quantify, or at least qualify, the impacts of vessel passage will then be useful as the ability of resuspended sediments to remain in the water column is determined primarily by current velocity and the size of the suspended particles, rather than the concentration of the suspended particles. Numerical simulations were carried out using simplified non-hydrostatic numerical models, and these show reasonable agreement to qualitative observations of the water level motion in the vicinity of the reefs. The simulations suggest that in certain areas, the fast-moving ferries may contribute significantly more to resuspension than large container vessels.

A detailed study was made of the sediment samples, coral mucus, and sediment cores to detect extracellular polymeric substances (EPS). However, no presence of EPS were found in any of the samples. In attempting to elucidate the reason behind the lack of EPS, we found bacteria genera in the samples that have previously been shown to produce compounds which suppress biofilm formation in marine sediments.

Figure 1: Hard corals produce mucus in response to sediment stress. Coral mucus binds to sediments on and around the corals as a means to keep coral tissue surface clean. As more sediments are trapped, the mucus-sediment aggregate sinks. This process enhances the retention of sediments on the coral reef and makes our waters more murky.

Future directions

Our findings describe key processes that influence the health of coral reef ecosystems in Singapore, using sediments as a case study. This also addresses a broader research arena that examines the effects of ecosystem impairment on their abiotic environments—a scope that is often not considered in the regular EIA processes in Singapore.

In that context, the design of EIAs and environmental monitoring and management programmes (EMMPs) with regards to spatial and temporal extent of modelling parameters and monitoring considerations has to be re-examined to advance sustainable development in Singapore.

With proper consideration of biota effects on the marine environment, the step forward should be the re-evaluation of impact intensity and ecological thresholds to environmental stressors in coastal ecosystems. Furthermore, with climate change–related fluxes to the marine environment, impacts and thresholds are likely to be dynamic. Having the capacity to predict and inform on the sensitivity of marine and coastal ecosystems will be immensely instructive for agencies overseeing marine operations such as dredging, to minimise their ecological footprint. An example of an application will be to guide the industry on setting the best window for dredging operations to minimise the risk of sediments damaging Singapore's sensitive coral reefs.

P32

OCEAN ACIDIFICATION IN SINGAPORE:

Assessing and monitoring the impact of peatland-derived dissolved organic carbon on the seawater carbonate system

Patrick Martin (PI)

Nanyang Technological University

Introduction

Ocean acidification is the 'other CO_2 problem': part of the CO_2 from human emissions dissolves into the ocean, forms carbonic acid, and thereby lowers seawater pH and the saturation state of calcium carbonate. Calcifying organisms, including corals, are likely to be affected most severely, but even non-calcifying organisms may be impacted. Across the open ocean, the rate of ocean acidification is a relatively simple function of atmospheric CO_2. In coastal seas, however, the extent and rate of acidification are far more varied, because the complexity of coastal carbon cycling can greatly amplify or dampen acidification. To assess the potential impacts of ocean acidification in coastal regions, it is therefore essential to understand local drivers of seawater carbon biogeochemistry.

Main findings

We found that important aspects of water quality in the Singapore Strait are controlled largely by input from rivers outside of Singapore. The monsoonal change in ocean currents then delivers waters with different water quality properties to the Singapore Strait at different times of the year. The input of dissolved organic matter from peatlands on Sumatra is a key factor that affects Singapore during the southwest monsoon period (May to September), when the ocean currents flow eastwards through the Singapore Strait to the South China Sea. We found that this organic matter has two main effects: first, 60–70% of it decomposes to CO_2 in the sea, which lowers seawater pH to values that are potentially harmful to corals. Second, the remaining 30–40% of peatland organic matter strongly absorb sunlight, especially at blue wavelengths of the light spectrum. This leads to a seasonally sustained decrease in the amount of sunlight underwater and in a shift of the available light to longer wavelengths that are less efficient for photosynthesis.

The seasonal acidification caused by peatland carbon will be amplified in the future, because the global-scale acidification of the open ocean will reduce the buffering capacity of the seawater that flows from the South China Sea to Singapore and Sumatra. This interactive effect may make the Singapore Strait particularly vulnerable to ocean acidification. Our work also shows that most of the dissolved

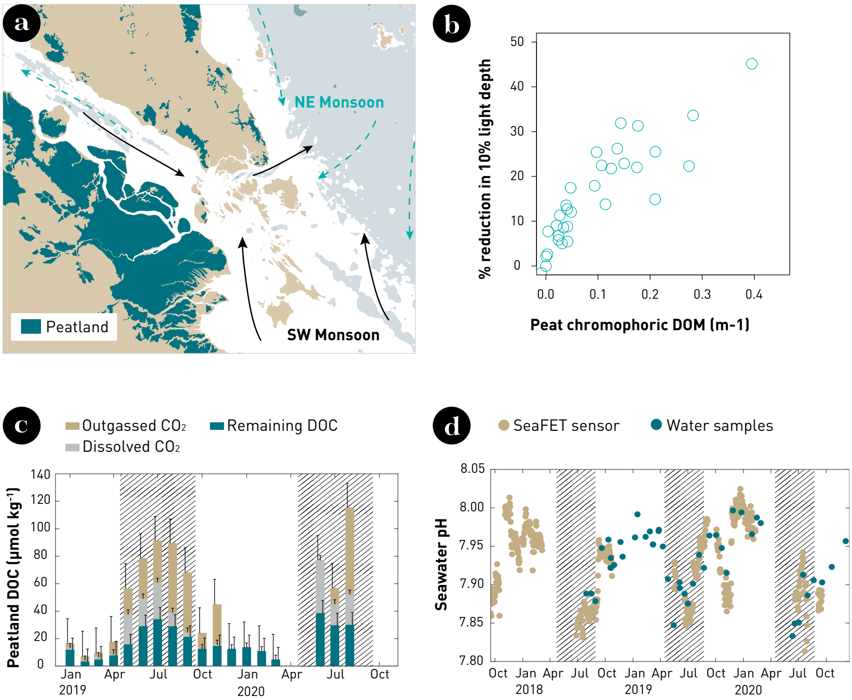

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Figure 1: (a) Dissolved organic matter from peatlands reaches Singapore during the southwest monsoon (May–Sept, shading in panels c and d). (b) The light-absorbing, or chromophoric, fraction of the peatland dissolved organic matter (DOM) significantly reduces the depth to which sunlight penetrates. (c) Carbon isotope data reveal that the majority of the peatland dissolved organic carbon (DOC) decomposes to CO_2 after reaching the sea, with part of the CO_2 outgassing and part remaining in solution. (d) The additional CO_2 from peatland DOC decomposition drives a seasonal decrease in pH to below 7.90. Figures 1a, c, and d modified from Zhou et al. (2021) *Journal of Geophysical Research: Oceans*; Figure 1b modified from Martin et al. (in press) *Marine Ecology Progress Series*.

organic matter delivered by tropical peatlands to the sea decomposes to CO_2, which is relevant for large-scale carbon accounting.

Our discovery that underwater light availability in the Singapore Strait is strongly controlled by peatland dissolved organic matter means that locally generated turbidity (e.g., from sediment resuspension) is only one factor contributing to light limitation. Light absorption by peatland organic matter contracts the depth of the euphotic zone further: without the peatland influence, the depth to which 10% of surface light reaches would be up to 5m, or 45%, deeper. The depth distribution of light-dependent organisms such as seagrasses and corals is hence controlled by both suspended sediments and dissolved organic matter. Suspended sediments might therefore be particularly damaging during the southwest monsoon, when light levels are already reduced by peatland organic matter.

Deforestation and drainage of peatlands may have increased the input of dissolved organic matter substantially. We estimate that roughly 30% of the seasonal acidification and roughly 25% of the reduction in light availability might be anthropogenic. Regional land-use practices are thus potentially important controls over water quality in the Singapore Strait.

Future directions

Through this project, we have collected what is likely the longest and most comprehensive time series of seawater biogeochemistry for any Southeast Asian shelf sea. The capacity we built will play a key role in the Marine Environment Sensing Network (MESN) programme, through which we will continue to collect critical environmental time-series data. Important questions that must be addressed in future include the physiological sensitivity of organisms in Singapore to acidification, and the relative importance of nutrient and light limitation for biological productivity.

P33

MICROBE-SEDIMENT INTERACTIONS IN THE COASTAL MARINE ENVIRONMENT:

Fate and transport of pathogens relevant to health and farming

Stefan Wuertz (PI)[1], Maria Yung (Co-I)[2]

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[2] *St. John's Island National Marine Laboratory*

Introduction

As global demand for seafood is increasing, aquatic food production has transitioned from being primarily based on wild capture of fishes to aquaculture. Yet the contribution of environmental factors to disease formation and reservoirs of the pathogenic bacterial species in the natural environment are poorly understood. This project addresses the fate and transport of one of the most important fish pathogens in Singapore, *Tenacibaculum maritimum*, at the sediment-water interface in coastal waters.

Main findings

First, a total of 59 coastal sediment samples from aquaculture and control sites were collected in the Johor Strait, and analysed together by 16S rRNA gene metabarcoding. The objective was to establish a baseline for sediment bacterial communities and the presence of pathogen-like sequences in the Johor Strait at sites impacted by aquaculture practices. Putative pathogen-associated sequences of *Mycobacterium* have been detected in all samples including non-aquaculture sites, suggesting a potential for mycobacteriosis, a common chronic and lethal disease in fish; in addition, sequences associated with the genus *Tenacibaculum* were found at one site.

To study the fate of *T. maritimum*, a type strain was grown in the laboratory and released in a controlled water-sediment experiment (Figure 1) along with enterococci, a microbial indicator of marine water quality, and bacteriophage P22, which serves as surrogates for other viral and bacterial fish pathogens (Figure 2). The research team has used a molecular assay for the detection of viable *T. maritimum*. The decay rates of target organisms in a stationary microcosm and two replicated flow-through mesocosm experiments were compared to determine whether decay rate constants obtained from incubation of stationary flasks without fluid exchange adequately reflect conditions in the natural environment (as approximated in the flumes). This is an important research question because flow-through conditions are almost never considered in decay studies of chemical and biological targets.

Figure 1: Flume mesocosms with water quality sensors. Six 2m-long rectangular flumes were seeded with sediments from areas not impacted by aquaculture; next biofilms were allowed to develop over a period of three weeks before adding the three target organisms. The panel in the bottom right corner shows multiple water quality sensors partially submerged in seawater for continuous monitoring of physicochemical water parameters.

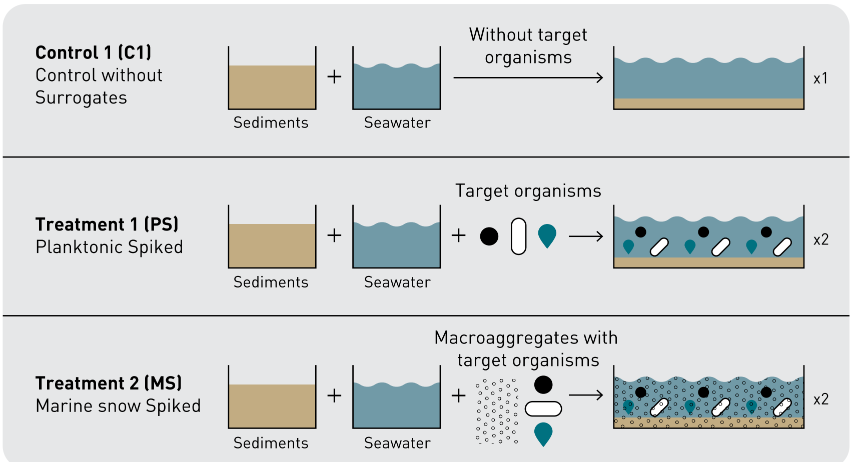

Figure 2: Experimental design for decay kinetics of target organisms in flume mesocosms. Overnight cultures of target organisms (planktonic or aggregated) were added to four acclimated flumes while the remaining flume act as a control with no addition of target organisms. All five flumes were operated for three weeks and sampled at several time points for sediment and seawater analyses.

Overall, marine snow facilitated microbial survival and persistence in sediments and seawater in both stationary microcosms and continuous-flow flumes. Sediments should be considered a sink and source of pathogens in the marine environment due to the higher persistence rate of all target organisms. Finally, *T. maritimum* can survive long periods in water and sediments, and this finding suggests a possible threat to fishes and human health.

Future directions

Future studies to benefit safer aquaculture farming practices should investigate if *T. maritimum* and viruses released back into the bulk water are able to infect healthy fish.

P39

ASSESSMENT OF IMPACT OF THE INVASIVE MUSSEL *MYTELLA STRIGATA* (BIVALVIA: MYTILIDAE) IN SINGAPORE

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[3] *National Parks Board Singapore*

Introduction

Shellfish are widely represented in many global invasive species databases. Bivalves are of particular concern as they are eco-engineers capable of significantly altering ecosystems and contribute to economic impacts. For example, infestation of bivalves on marine/aquaculture installations can cause reduced harvest for economically important shellfish, and reduce seawater intake in cooling towers for coastal power plants. As a major transhipment hub in Southeast Asia, Singapore is vulnerable to bio-invasions. In 2016, a new invasive mussel *Mytella strigata* was extensively reported in Singapore's waters. This mussel is native to Central and South America, and exhibits wide temperature and salinity tolerances. It has been recently recorded in the Philippines, Thailand, and India, where there are concerns over its establishment and potential impact on aquaculture. Following reports of large aggregations of *M. strigata* occurring on local mudflats, this study conducts an assessment of the extent of infestation of the invasive mussel in nature areas in Singapore and its interactions with native species. The goal is to provide information to enable managers to identify priority areas and practical targets for management. Field surveys have been carried out in collaboration with public volunteers as part of citizen science engagement.

Main findings

Populations of *M. strigata* have been found on mudflats, mangroves, and hard artificial structures (e.g., pillars, monsoon drains) along nature areas in Sungei Buloh Wetland Reserve (SBWR), Lim Chu Kang, Kranji, Mandai, and Sembawang. In particular, dense mussel colonies have been found in Kranji, SBWR, and Sembawang. No mussels have been detected on the mudflats or shores at Pasir Ris Park, Changi Beach Park, Pulau Semakau, Sarimbun, and the Southern Islands. Recommendations for mitigative measures have been proposed.

In terms of species interactions, only low numbers of predatory muricid snails have been found on *M. strigata*. This study documents the presence of *M. strigata* on mangrove horseshoe crabs. They are attached mainly on the underside of the horseshoe crab. However, the number of crabs infested with mussels is not high.

From online surveys conducted as part of the citizen science engagement on invasive species management, respondents have indicated the need for actions to be taken to manage the impacts documented in nature areas, including having a specific law on invasive species management. The study also recognises the need for more outreach and education on problems caused by invasive species.

A dense bed of invasive mussels, *Mytella strigata*, encountered at Kranji.

Future directions

This study notes that the International Maritime Organization (IMO)'s guidelines to minimise transfer of invasive species will contribute positively to reducing infestations as well as improve ship performance. In addition, it is proposed that a unified national strategy is needed to address and manage marine invasive species. Border controls will assist to minimise risks of introductions through major pathways of shipping, seafood/aquarium trade, and aquaculture. It is recommended that Singapore implement the IMO's Guidance on Port Biological Baseline Surveys, which provides a simple framework for the surveillance needed for the detection of invasive species.

P42

MONITORING OF ARCTIC MELT RATES

Mandar Chitre (PI)

Acoustic Research Laboratory, Tropical Marine Science Institute, National University of Singapore

Introduction

The Arctic is the focal point of global climate change. This has spurred an accelerating rise in global sea level, of which a significant component is attributed to ice-loss from glaciers and ice caps. Sea-level rise has impacted coastal ecosystems worldwide and poses an increasing risk to coastal states. As Singapore is a low-lying and densely populated state, it is particularly vulnerable to the effects of sea-level rise. Melting Arctic ice also signals the opening of new trade routes that can affect Singapore's standing as a nodal port in the region. Thus, Arctic ice-melt monitoring is of particular interest for Singapore, which is an observer on the Arctic Council.

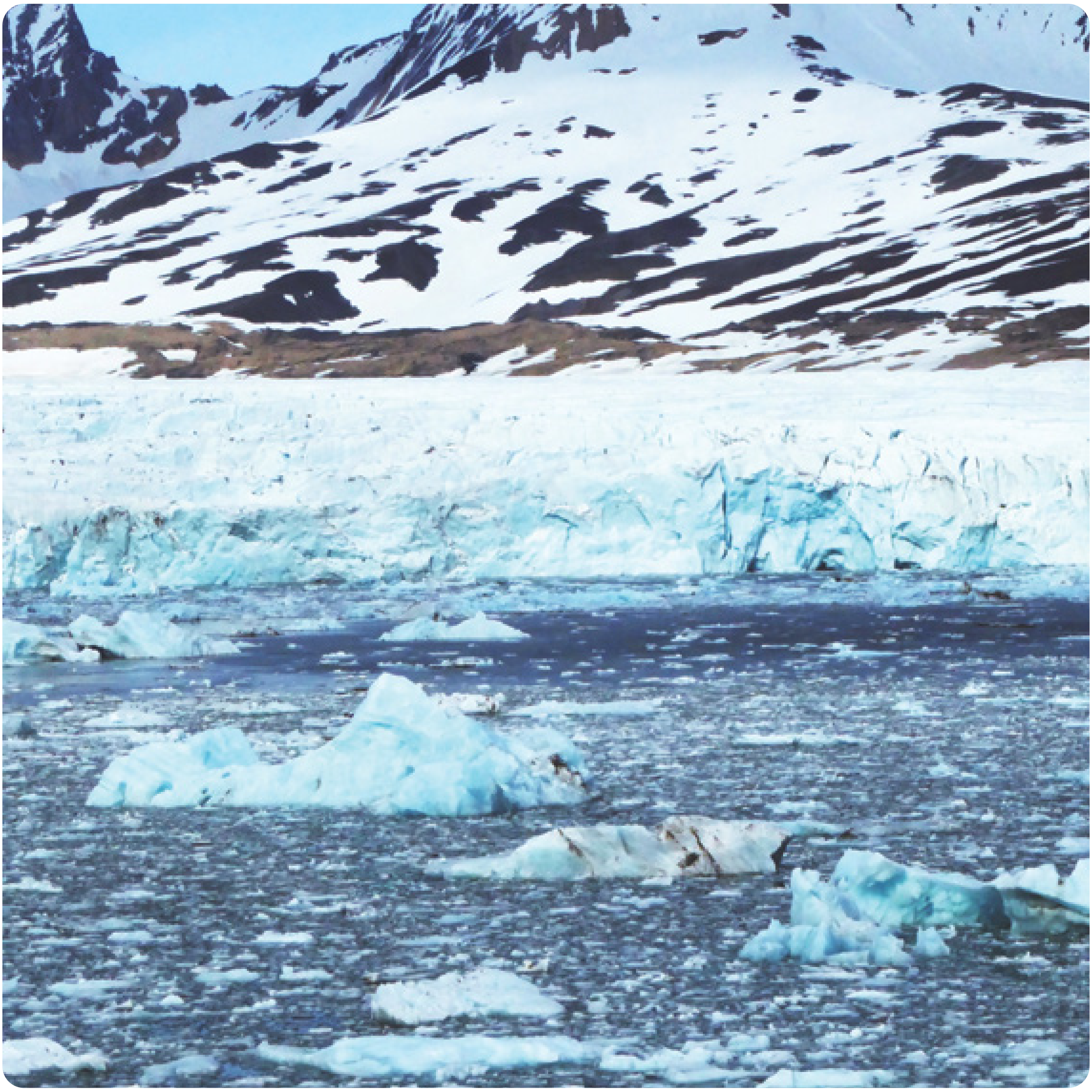
At the glacier-ocean interface, the underwater melting of glacier ice produces a sound similar to 'frying bacon' due to the explosion of bubbles, which provides us an opportunity to estimate the amount of melting. Passive acoustic monitoring (PAM) techniques are suitable for extracting information on the climate change–related mechanisms in these noisy glacial bays, because sound data is simple to acquire, covers a large area, and can facilitate long-term monitoring. This is the focus of this project.

Main findings

We have undertaken a field expedition to Svalbard, Norway, with scientists from the Scripps Institution of Oceanography and the Polish Academy of Sciences, and collected acoustic recordings using a vertical array of sensors from four glacial bays. This is the first such study that is acoustically well-instrumented enough to help us understand the acoustic field at glacial bays in detail. The data has revealed several exciting insights into the submarine melting at glacial bays. We have shown that the sound emitted has a vertical directionality, i.e., only the melting at the shallowest region of the glacier-ocean interface is noisy. Acoustic modelling can capture many aspects of the sound propagation in the channel, therefore this sound shows promise as a source of information to estimate the melt rate. Acoustics can also characterise other events in the bays such as passing of ice pieces and calving. The challenges involved in this include: (1) tackling the acoustic distortion due to the complex thermohaline structure of the water channel, and (2) understanding the physics of the bubbles released by melting near the glacier boundary and distortion caused by them. These are the focus areas for our future research.

Future directions

Techniques developed out of this research can help towards building a monitoring system that can operate in the harsh environment of the Arctic. Such long-term estimates of melting can help improve predictions on sea-level rise, which pose an increasing risk to Singapore. The project has also opened doors for Singapore to collaborate with other world-class institutions working on this topic, such as Scripps Institution of Oceanography, and the Institute of Geophysics, Polish Academy of Sciences.



↑ Hansbreen glacier, Svalbard, is one of four glaciers where we collected acoustic data for this project.

P45

PREVALENCE OF ANTIBIOTIC RESISTANCE GENES (ARGs)

in marine sediments along the Johor Strait of Singapore

Stefan Wuertz (PI)[1], Maria Yung (Co-I)[2]

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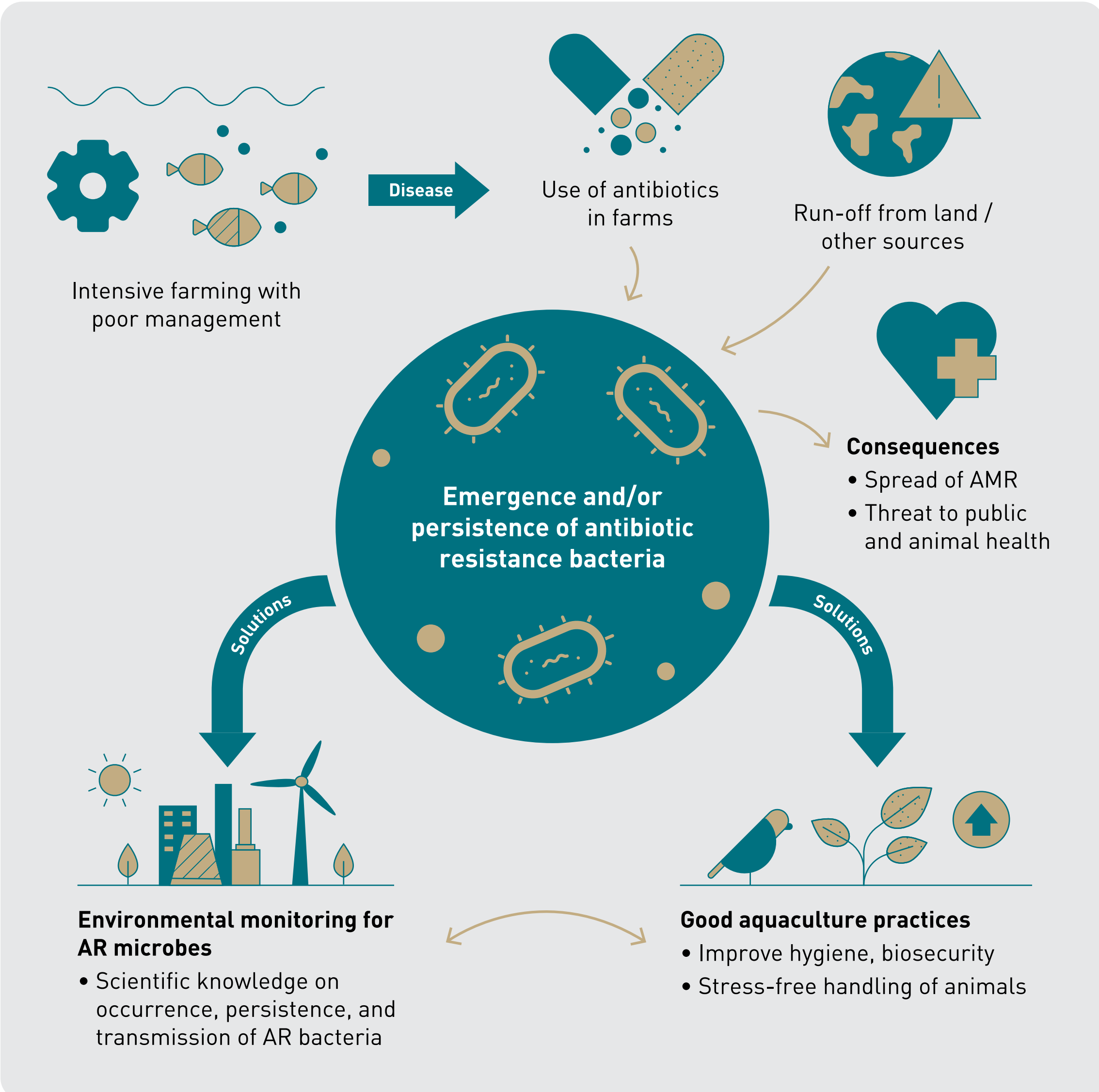
[2] *St. John's Island National Marine Laboratory*

Introduction

The decline in global wild fisheries has fuelled an increasing demand for intensive aquaculture practices. Antibiotics or antimicrobial compounds are still being used in countries with major aquaculture industries. Other sources of antibiotics in the environment include run-off/leaching from livestock farms and municipal waste treatment plants. The presence of antibiotics is known to select for antibiotic resistant bacteria, and antimicrobial resistance (AMR) is emerging as a global threat to public health. This project addresses the prevalence of antibiotic resistance genes (ARGs) in coastal marine sediments along the Johor Strait in Singapore. A shotgun metagenomic sequencing approach was used to screen a wide spectrum of ARGs.

Main findings

A total of 67 samples was sequenced and has generated approximately 66gb of metagenomic data. The screening method approach was highly stringent, allowing the selection of ARGs with at least 98% nucleic acid identity to those known in the current database. Results indicate that such ARGs occured at very low abundance across all sediment samples analysed, with a positive hit rate ranging from 10^{-4} to 10^{-6}%. Time and sampling location within the Johor Strait did not influence the abundance or profile of ARGs detected. Collectively, the western Johor Strait contained more ARGs compared with eastern Johor Strait; however, due to their low prevalence and abundance, no statistical analysis was conducted. Major antibiotic gene classes detected in the western Johor Strait included those that confer resistance to tetracycline, aminoglycoside, and lincosamide antibiotics as well as *rpo* and macrolide-efflux genes. Chloramphenicol and MLSB resistance, and ABC transporter genes were also present, among others. Tetracycline resistance was the most abundant gene class in sediment samples and the genes identified were closely related to *Clostridium perfringens*, *Enterococcus faecalis*, *Staphylococcus aureus*, *Streptococcus suis*, *Streptococcus pyogenes*, and *Gardnerella vaginalis*. Overall, study results suggest that antibiotic resistance genes are present at very low levels in the Johor Strait sediments and are not elevated at aquaculture sites.



Future directions

Given plans for Singapore to expand coastal aquaculture activities, routine monitoring of antibiotic resistance genes in coastal sediments can act as a sentinel for any surge in the presence of antibiotic-resistant microorganisms and their resistance genes. This will help safeguard Singapore's marine resources and prevent resistance genes from entering aquaculture facilities and thus the food chain.

A colourful nudibranch, *Hypselodoris* sp.

Project Summaries

COASTAL ECOLOGICAL ENGINEERING (CEE)

P05

ECOLOGICALLY ENGINEERING SINGAPORE'S SEAWALLS TO ENHANCE BIODIVERSITY

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Introduction

By the next decade, approximately three quarters of the world's population will reside in coastal zones. In addition, sea-level rise and more intense storms have already resulted in an urgent need for shoreline protection. As a result, man-made coastal deferences such as seawalls are quickly, and on a global scale, becoming the primary means of mitigating the risks of flooding and erosion. Seawalls, however, differ from natural shores in fundamental ways. They are usually very steep, increasing the effects of wave impact and compressing the intertidal zone. Seawalls have few microhabitats (e.g., pits, rock pools, overhangs, and crevices) and little structural complexity. They are frequently made from materials that may not be well-suited for colonisation and/or exhibit thermal properties that result in unfavourably high temperatures when the tide is down (Figure 1).

Despite these adverse consequences, only recently have researchers examined the ecological impacts of seawalls or suggested ways to boost biodiversity. Realising that these structures are permanent, there is now substantial interest in maximising their ecological value. Designing urban infrastructure in a manner congruent with ecological principles is known as ecological engineering, and this concept lies at the core of our project. We approached the challenge of how seawalls can support an abundant and diverse array of species through a unique synthesis of ecology, materials science, microbiology, and fluid mechanics.

Main findings

To date, the great majority of research on the ecological engineering of artificial shorelines has been conducted in temperate regions. While we can learn from this research, studies in tropical contexts are urgently needed. To better understand the current status of Singapore's extensive artificial coastal defences, we carried out multiple surveys to summarise the physical characteristics of numerous seawalls

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Figure 1: (a) Typical granite rip-rap seawall in Singapore (at Pulau Hantu). (b) Conducting surveys at Changi Bay.

(and these helped validate three-dimensional digital models). We also monitored the species richness, abundance, and community composition found on seawalls and natural rocky shores and showed they are significantly different. As artificial shores elsewhere have been reported to support invasive species, we undertook targeted surveys for non-native species at seven seawall sites, but only found one 'possibly introduced' species (*Siphonaria guamensis*).

To better understand the drivers of seawall ecological communities, we examined predator–prey relationships through a series of field-based manipulative experiments. We also investigated how human-engineered hydrodynamic regimes affect cryptic macroinvertebrate assemblages on urban artificial shorelines. Stable isotope analyses were applied to elucidate the diets of the common species (an approach that has never been performed on artificial coastal structures). The thermal ecology of seawalls was investigated, and field monitoring of temperatures led to the development of a new technology (Robonerites) to record organism-perspective temperatures. These data were then used to create a numerical programme to simulate the temperature variation on a typical seawall that showed how the wet and dry areas of seawall together with extreme temperatures affect the maximum habitable zone for an intertidal marine ecosystem. Manipulative experiments identified the thermal preferences of selected invertebrates to see if this aligned with their distribution in the field.

This fundamental knowledge was used towards our second objective of determining how existing seawalls can be manipulated to enhance biodiversity. In most cases it is not feasible to replace coastal armour with 'softer' alternatives. It is, however, possible to retrofit them with topographically complex blocks or tiles (e.g., BioBoss) made of materials that encourage settlement by marine organisms (Figure 2). We demonstrated the significant effects of complexity and structural component type on intertidal diversity and community composition by fixing hundreds of these tiles on seawalls around Singapore. We tested the effects of water-retaining features, their hydromechanical properties, and their ability to support algal growth and thus other communities such as fish. Our results show that, at multiple scales, greater topographic complexity leads to greater biodiversity, and a meta-analysis revealed that this is partly due to predation intensity being reduced in complex habitats. We applied these finding to create a range of new designs for different conditions, including WedgePools for vertical seawalls (Figure 2).

After determining that enhancement tiles work, we examined the effects of habitat area (density of tiles) and spatial arrangement (single large, several small, and individual tiles spread out) to optimise installation. Results showed that the several small groups of tiles covering 15% to 20% of the seawall led to the greatest

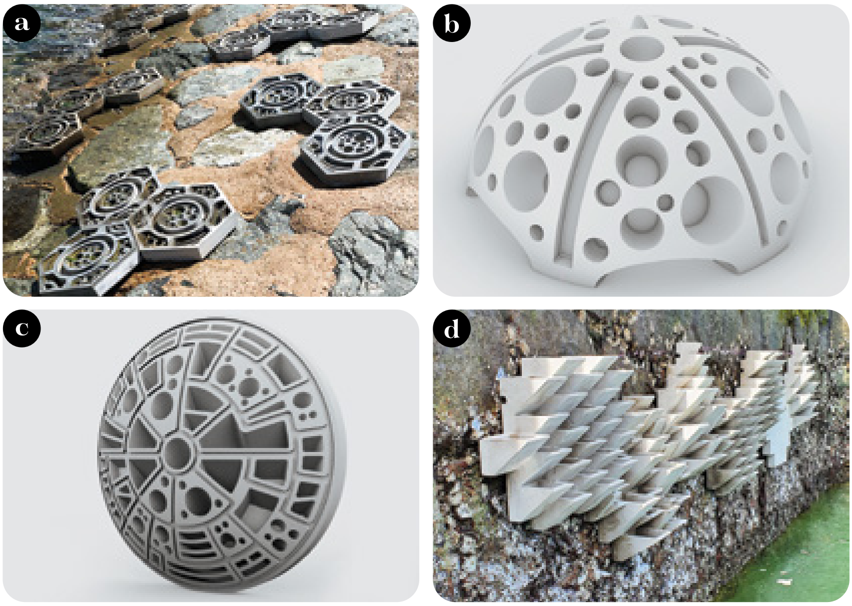

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Figure 2: Some marine biodiversity enhancement designs to arise from our study: (a) for sloping seawalls, BioBoss2; (b) for individual boulders, RockUrchin; (c) for intertidal canal walls, LifeCircle; (d) for vertical seawalls, WedgePool.

overall species richness. Combined with a new composite tile design, BioBioss2, we established a tile configuration suitable for large-scale implementation and, working with Stephen Caffyn Landscape Design, installed this at Changi Bay. This configuration was also tested for its effects on wave runup and rundown along the seawall surface using a physical model with a scale of 1:4 in a flume set-up. Overall, the effect of the tiles was not significant for long period waves but they can reduce the wave runup by 10% for realistic waves in Singapore. This is beneficial for the protection of the land behind seawalls from a coastal engineering perspective. Using the OpenFoam open source CFD code, numerical studies have also been carried out to examine the effectiveness of different seawall designs and surface roughness in reducing runup heights and overtopping—a tool that will be useful for the future design of new coastal infrastructure.

Fundamental to the design of the enhancement tiles is the material they are made from. We examined the influence of natural stone and concrete substrates on the settlement and growth of marine organisms. The natural stones were limestone, marble, two types of sandstone, and granite. Microbial settlement and biofilm composition were quantified to determine if the different substrates could be used to regulate the settlement of macroorganisms. From field-relevant assays, the type of stone did not significantly impact biofilm composition or microbial settlement. Parallel studies examining the effects of tile material on invertebrate fauna and macroalgae also showed no significant effects for fauna and only weak effects for algae.

As an alternative approach, biodegradable polymer films were applied to the stone surfaces. These are also designed to be readily retrofitted onto existing structures. The polymer coatings mask the physicochemical properties of the underlying stone and can serve as a vehicle for introducing bioavailable polysaccharides, such as chitin, mannitol, or calcium carbonate fragments. The addition of these actives in the polymer coatings influenced the composition of initially formed marine biofilms. However, over a period of four weeks, the influence of substrates was diluted to immeasurable levels.

Coral larval assays showed improved larval settlement and juvenile maturation on natural limestone substrates, as well as those with polymer coatings containing calcium carbonate (Figure 3). These biodegradable polymer coatings may also serve to facilitate the seeding and long-term culture on previously unconducive substrates of juvenile coral, which can subsequently be transplanted to a desired location. The filing of a patent has been initiated, covering the innovation of retrofitted polymer coatings that may enhance marine biodiversity on existing anthropogenic structures.

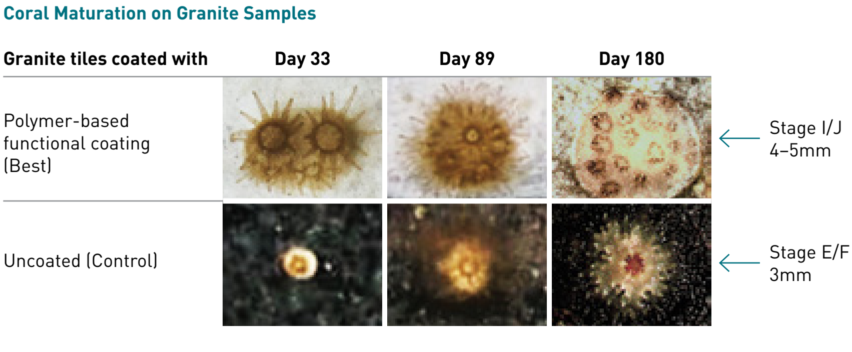


Figure 3: Juvenile coral maturation on polymer coatings with bioattractant additives.

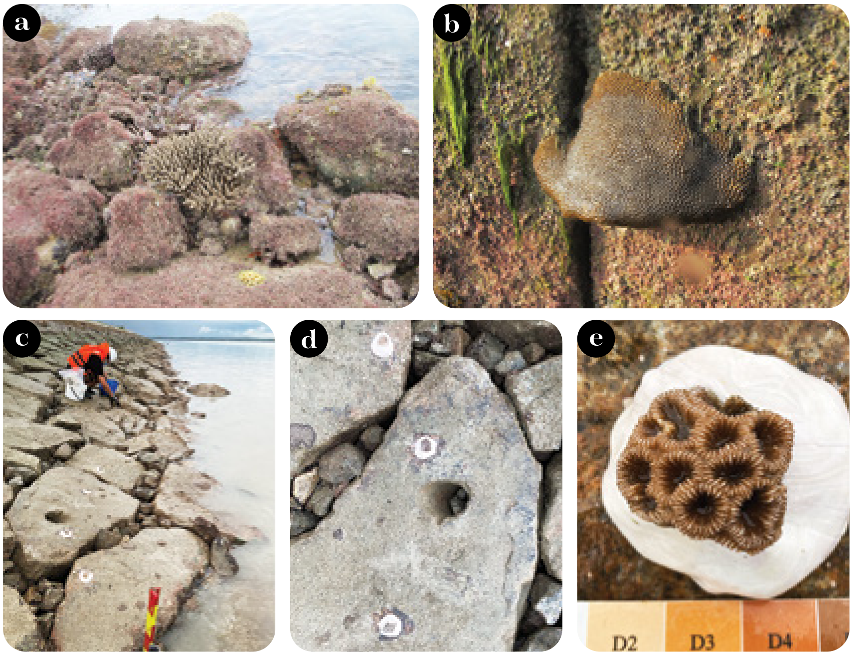
Encouraging coral settlement was complemented by direct coral transplantation (Figure 4). First, the diversity and distribution of hard corals that have naturally settled on existing seawalls in Singapore was determined. We found that nearly half of all hard coral species found on natural reefs also occur on seawalls, albeit in lower densities. In addition, we observed that there is ongoing recruitment of coral juveniles on newer seawalls (Figure 4). Hard corals are generally more diverse and more abundant on sloping seawalls in comparison with vertical seawalls. These findings suggest that hard corals are not only able to settle and grow on seawalls, but also form a distinctive component of sessile fauna in the low intertidal areas of seawalls.

A substantial proportion of these hard corals are amenable to fragmentation and husbandry in aquarium conditions. Optimal conditions for survival (light, temperature, salinity, additional nutrition, species interactions) were established for long-term mariculture of coral fragments at the St. John's Island National Marine Laboratory. Some species appear to tolerate high temperatures above 31°C for more than two months, which was a surprising finding. Fragments of certain coral species could be cultured together, but not others. Together, these results provide the foundation knowledge required to scale up the land-based culture of coral fragments, either in flow-through or recirculating aquaria, to support future transplantation efforts.

Although corals are generally found in the subtidal environment, some can withstand certain levels of air exposure when the tide goes down (and the associated increase in temperature). To explore this further, we tested the physiological and gene expression responses to corals to air and heat exposure under experimental conditions. Further, we examined within-species (i.e., among-genotype) responses to see whether fragments collected from particular colonies (genotypes) coped better with being out of water. We found that the species *Pocillopora acuta* is able to tolerate air exposure for up to two hours, suggesting its potential to serve as a 'starter species' for transplantation efforts on seawalls.

Having established that a wide range of hard corals can live on seawalls, and that many survive fragmentation, we constructed a database that defines the physical and biological requirements of each species, in the context of habitat, fragmentation, and aquarium husbandry. The database has formed the basis of a 'selection matrix' to prioritise which hard coral species are best suited for transplantation to seawalls of different configurations and to fit prevailing physical and biological conditions. The selection matrix is being developed into a web-based application that can be made available to industry and nature conservation groups.

In addition to producing more than 40 research papers and over 40 conference presentations, the seawall project published a number of major reviews on urban coral reefs in Southeast Asia, urban marine ecology as a discipline, the history of shoreline defences globally, and shoreline management using eco-engineering.



→ Figure 4: Corals on seawalls. (a) Naturally recruited branching and other corals amongst turf algae in the intertidal zone at the base of a sloping seawall; (b) naturally recruited juvenile massive coral (*Porites lutea*) on a vertical seawall; (c, d) coral fragments being transplanted onto a sloping seawall at low tide; (e) close-up view of a healthy coral fragment (*Goniastrea retiformis*; approx. 3cm diameter).

Future directions

The overall aim of this project was to enhance native biodiversity on coastal defences in Singapore using ecological engineering principles. This work represents the first interdisciplinary seawall eco-engineering study in the tropics, integrating the expertise of ecologists, engineers, biologists, and material scientists. Our ultimate goal is to generate science-based solutions with scalable, transferable technologies for a pernicious problem. While we have made a great deal of progress, there is still work to be done.

Upscaling is perhaps the greatest challenge. To consider designs for larger sections of new seawall and optimise the biodiversity return on investment, we need to extend our understanding of complexity–biodiversity relationship to larger spatial scales, beyond those covered by existing experiments. We will use the findings from our ongoing remote-sensing studies of artificial and natural shoreline complexity, and experimental studies of larger scale features to inform the design of future seawalls. This research aspires to influence coastal design to include complexity across a wider range of scales, broadening the available niches and increasing the biodiversity benefit.

The feasibility of upscaling any ecological engineering solution should be evaluated using a cost-benefit analysis, where the potential financial and environmental costs of implementation are weighed against the expected ecological benefits. As our results indicated little difference in biodiversity enhancement among construction materials, the choice of which to use becomes one of production cost, strength and durability, availability of materials, carbon footprint, and broader environmental impacts, etc. It is critical to determine the costs and benefits of stone and concrete, including green concrete, for coastal ecological engineering in Singapore.

Coral transplantation holds much promise in the context of marine habitat enhancement in Singapore. The project has narrowed major gaps in the practicalities of the process: which species fragment well, how to keep fragments healthy, what species/genotypes to transplant, and where to transplant the fragments. A crucial step forward is to determine how transplanted fragments will perform over a longer period of time on seawalls at different locations, and especially whether they can attain reproductive success. These data can then be fed back into the coral selection matrix to strengthen its utility. Seawalls, instead of natural reefs, can in turn be a source of coral fragments for subsequent transplantation in Singapore. The use of mature colonies as sources of gametes or larvae for large-scale coral transplantation on new and existing seawalls will be key to enhancing genetic diversity and ease of collection. This will depend largely on our ability to obtain eggs and sperm from adults in the aquarium at will. Artificial induction of these reproductive processes in the aquarium through provision of suitable genetic and/or environmental cues is key to this endeavour.

Future research should identify the full range of ecosystem services that eco-engineering shorelines can provide. In Singapore, numerous studies have examined the role natural habitats play in providing ecosystem services; however, we have little knowledge about how and when these services are associated with engineered coastlines, and therefore how society may expect to receive these benefits in the future. Assessing the value of ecosystem services allows for more weight to be given to them and their importance in policy decisions. Hence, we should investigate what services are currently being provided by Singapore's engineered shorelines, the potential for engineered shorelines to provide greater services in the future, and how shoreline management strategies can be created to optimise service provision.

'Collaborating with the MSRDP has been a great experience. It has resulted in tailored marine biodiversity enhancement solutions so that we are able to implement in our projects around Singapore.'

Stephen Caffyn
Principal
Stephen Caffyn Landscape Design

For Singapore as a whole, a smart digital coastal database should be established that can be used by various parties such as government agencies, researchers, engineering companies, and nature groups. Good quality data are essential if we are to produce reliable prediction results for coastal areas potentially affected by severe storm surge or extreme tidal flooding. With a better understanding of these threats, more effective solutions can be found. For example, characterising coastal waves around Singapore is a fundamental yet missing piece of information for the coastal protection of Singapore. To resolve this, it is necessary to deploy wave measurement buoys as early as possible. For a resilient coastal defence against tidal flooding and storm surges with rising seas, new coastal infrastructure should be designed in an integrated manner. Incorporating living components, from subtidal to intertidal to terrestrial, can help mitigate flooding risk. For example, in addition to some of the solutions already mentioned, elevated coastal expressways and coastal park boundaries can be designed with features such as dense vegetation as secondary or tertiary natural defences.

As natural coastlines are globally being replaced by anthropogenic structures, a concerted and cohesive effort is required if shoreline biodiversity is to be conserved and ecosystem services maintained. Creating national-relevant and future-ready innovative seawalls that host a diverse array of native species with positive effects on neighbouring habitats and an overall increase in ecosystem resilience is an achievable goal. These sustainable blue infrastructure designs will improve aesthetics, provide more green space, and ultimately lead to a more liveable city.

P43

HORIZON MAPPING:

An integrated concept plan for St. John's Island

Jani TI Tanzil (PI)

St. John's Island National Marine Laboratory; Tropical Marine Science Institute, National University of Singapore

Introduction

The Horizon Mapping study was initiated under the MSRDP to advise on the future of St. John's Island, and surrounding islands and waters (henceforth, collectively known as the SJI Complex). This consisted of a scoping study that reviewed critical scientific, ecological, cultural, and historical information about the SJI Complex, as well as stakeholder surveys and engagements. Stakeholders engaged include members of the public, NGOs, researchers, and agencies (e.g., Sentosa Development Corporation, Singapore Food Agency, Urban Redevelopment Authority, National Parks Board, Centre of Liveable Cities, Maritime and Port Authority of Singapore, and Public Utilities Board).

An urbanised coastline

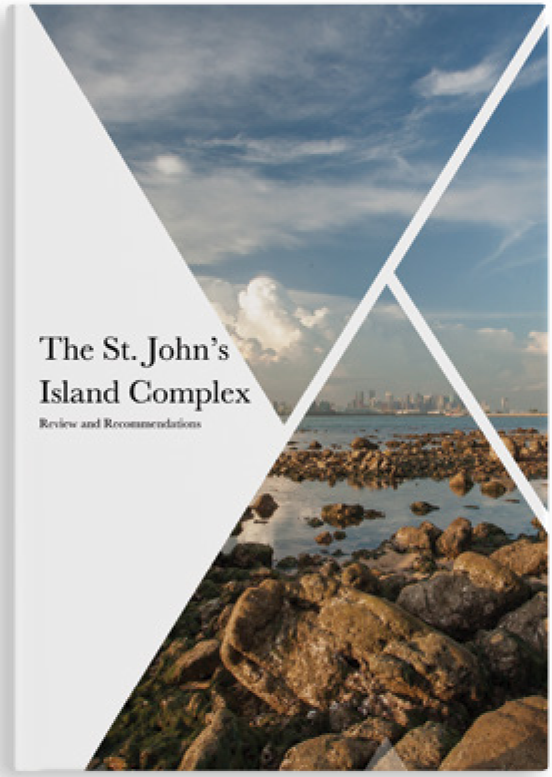


Figure 1: A comprehensive study of critical scientific, ecological, cultural, and historical information for the SJI Complex, providing a sound foundation for the recommendations to build the SJI Complex into a hub for marine science research, education, and eco-innovation.

'Sentosa Development Corporation (SDC) congratulates Dr Jani and her team at St. John's Island National Marine Laboratory on the completion of the concept plan for the St. John's Island Complex. The concept plan will be a useful point of reference in the making of any future plans for St. John's Island. We are pleased to note SJINML's ambitions to be a leading hub for marine science research, education, and eco-innovation to promote Singapore's long-term environmental, socio-economic, and resource resiliency. We thus look forward to exploring opportunities with SJINML to expand educational offerings on St. John's Island, as part of SDC's efforts to extend the Sentosa getaway and our learning journeys to the neighbouring Southern Islands.'

Jacqueline Tan
Assistant Chief Executive
Sentosa Development Corporation

↑

Figure 2: A proposed zoned land-use map is included in recommendations for the SJI Complex to become a mixed-use ecosystem that improves the quality of living for Singaporeans and contributes to the marine economy, as well as meeting local and international goals (e.g., the Singapore Blue Plan, the Nature Conservation Master Plan, United Nations Sustainable Development Goals etc.,).

'On behalf of URA, I am very appreciative to Dr Jani TI Tanzil and her team at St. John's Island National Marine Laboratory for taking the time and effort to draw up a concept plan for the St. John's Island Complex to be a hub for marine science research, education, and eco-innovation, which in turn promotes Singapore's long-term environmental, socio-economic, and resource resiliency. SJINML is one of the key stakeholders in St. John's Island (SJI), and the concept plan will be a useful point of reference for future reviews of land use plans for SJI.'

Daniel Soh
Executive Planner
Physical Planning (Central West)
Urban Redevelopment Authority

Future directions

Based on this scoping study, we recommended that the SJI Complex be known as Islands of Eco-innovation, and we outlined opportunities for its transformation as a hub for eco-innovation, research, and environment education. These recommendations are elaborated in the Horizon Mapping project's book, *The St. John's Island Complex: Review and Recommendations*, as well as on its microsite that shares more about the SJI Complex. The Our Southern Islands microsite (https://www.southernislands.sg/) also serves as an aid for environment education, and aims to create more awareness about the SJI Complex in general.

→

Intertidal seagrass at Bendera Bay, St. John's Island.

https://www.southernislands.sg/

An unidentified nemertean worm collected from Singapore

Project Summaries

MARINE TECHNOLOGY AND PLATFORMS (MTP)

P01

DEVELOPMENT OF A MOBILE MICROFLUIDIC PLATFORM *IN SITU*

and real-time monitoring of microbial pollutants in ballast water

Sungwoo Bae (PI)[1], Sung-Yong Park (Co-I)[2]

[1] *Department of Civil and Environmental Engineering, National University of Singapore*
[2] *Department of Mechanical Engineering, National University of Singapore*

Introduction

Faecal contamination is a serious threat to public health in both developing and industrialised countries. Diverse groups of enteric pathogens transmitted through human and animal faeces can cause outbreaks of waterborne disease. The threat to human and environmental health posed by faecal contamination is usually evaluated by measuring the concentrations of faecal indicator bacteria. These bacteria, such as faecal coliforms, *Escherichia coli*, and *Enterococcus* spp., are monitored by culture-dependent methods that require a microbiological laboratory. A major drawback of culture-based monitoring is that cultures must be incubated overnight, which delays the results and hinders early warnings and the timely implementation of measures to control or mitigate contamination. To address the limitations of the culture-dependent methods, DNA-based approaches like the polymerase chain reaction (PCR) have been used to rapidly assess microbial contamination in an environment. However, monitoring faecal indicator bacteria using PCR requires access to a sophisticated laboratory, skilled personnel, and expensive equipment, again preventing rapid assessment of water quality in the field. In this project, we developed a novel Lab-On-Smartphone platform to detect and quantify faecal indicator bacteria in environmental water.

Main findings

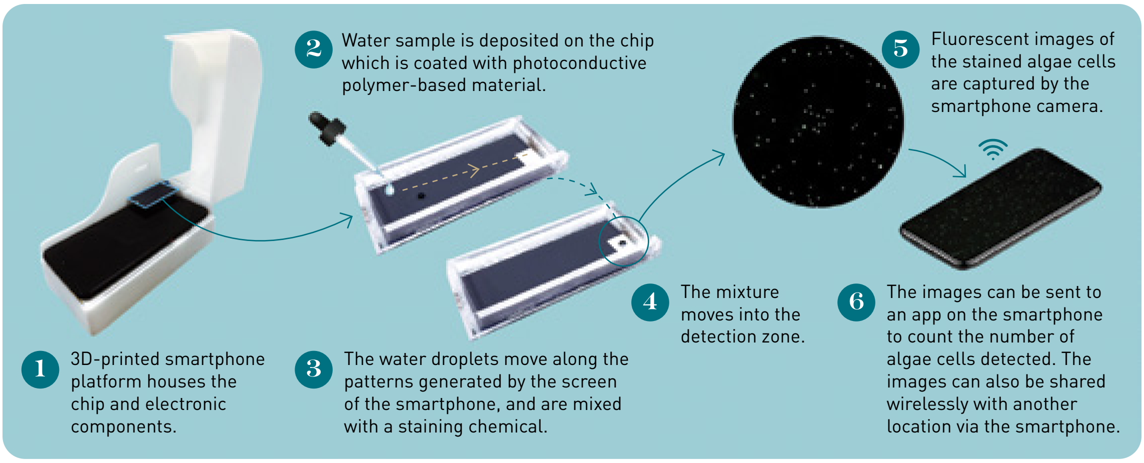
A Rapid quantification of faecal indicator bacteria in water using the most probable number–loop-mediated isothermal amplification (MPN-LAMP) approach on a polymethyl methacrylate microchip

We developed a rapid on-chip gene quantification method based on loop-mediated isothermal amplification (LAMP) PCR. The LAMP assays can measure the target genes of the faecal indicator bacteria, including *E. coli* and *Enterococcus* spp., using the most probable number (MPN) approach. The colorimetric LAMP assay allows for naked-eye observation of the PCR reaction with as few as four gene copies per well. When the reaction ends, MPN measurement of positive outcomes on the white-based polymethacrylic acid microchips provides the concentrations of the target genes of faecal indicator bacteria with a confidence interval. We validated the MPN-LAMP approach by obtaining a strong correlation between the results of the MPN estimations and quantitative PCR analysis. Moreover, the MPN-LAMP approach was used to quantify faecal indicator bacteria in water samples collected from freshwater reservoirs, a beach, a farm, and sewage. Our research demonstrates that the MPN-LAMP method enables us to easily and quickly quantify faecal indicator bacteria in environmental samples without expensive PCR instruments.

B An automated 3D-printed smartphone platform with an optoelectrowetted microfluidic chip for on-site monitoring of viable algae in water

Figure 1 shows a schematic of the 3D-printed smartphone platform that detects viable algae in marine and freshwater. We developed a 3D-printed smartphone platform integrated with a light-driven microfluidic chip that works on the principle of optoelectrowetting. This microfluidic chip not only allows multiplexed drop-wise functions such as droplet transportation, merging, mixing, and immobilisation on a detection zone, for on-chip water sample preparation, but also fluorescent detection and counting of target algae cells using a commercially available smartphone. Two freshwater algae (*Chlamydomonas reinhardtii* and *Microcystis aeruginosa*) and two marine algae (*Amphiprora* sp. and *Cylindrotheca closterium*) were employed to validate the 3D-printed smartphone platform in this study.

Figure 1: Schematic of 3D-printed smartphone platform.



Future directions

Our plan is to develop a portable, affordable, and 'sample-to-answer' platform for early and rapid detection of food-borne pathogens. The platform will be integrated with a smartphone that uses remote settings to inspect the presence of food-borne pathogens and enables prompt decision-making to eliminate the problem. The platform, named Lab-On-Smartphone (LOS), will be inexpensive and easily operated with a graphical user interface. The LOS platform serves as a mobile and field transportable laboratory to facilitate diagnostic testing on-site and during the import process. The LOS platform consists of a portable PCR device, a microfluidic chip, and a smartphone. The LOS platform offers a portable, affordable, and user-friendly platform that will meet the need for a rapid-detection device for food-borne disease detection in Singapore.

P08

A CROSS-DISCIPLINE USER-FOCUSED DATA MANAGEMENT PLATFORM

for data collected under the MSRDP

Seng Keat Ooi (PI)
Previous PIs: Tsai Min Sin, Esther Clews

Tropical Marine Science Institute, National University of Singapore

Introduction

METIS (Marine EnvironmenTal Information System) is a cross-disciplinary user-focused data management platform for marine science data. It is accessible to registered users at https://emid.nus.edu.sg/METIS/. METIS aims to promote cross-theme sharing, integrated management, and visualisation of data collected separately by each theme. METIS is intended to embed individual programs within the National Research Foundation MSRDP call, as well as to enable and anchor research data and outcomes, in a manner that promotes the transition from multidisciplinary to truly cross-disciplinary science.

Researchers may upload data to METIS via two modules: (1) Data Bank, and (2) Dynamic Database. The Data Bank is intended to be a repository for static or semi-static data, whereby data sets are uploaded and/or downloaded in their entirety. Relevant data can be identified through intuitive search functions and metadata reviewed for suitability and access. The Dynamic Database provides features for on-the-fly filtering and selection of data for both visualisation and extraction, and is intended to be the main avenue for data sharing and transmission on ongoing projects.

Figures 1 and 2 show the map and graphing features of METIS. The map shows an example data set in which sampling stations are displayed as map markers. The graph shows the same data set of monthly averaged temperature data at various sampling stations within a chosen month.

Main findings

In developing the platform, we found that:

- User-friendliness was key in attracting users to the platform. This was achieved mainly through contextual help that is easily accessible on the user interface. This cuts down the need to rely on lengthy user training and reading wordy user manuals.
- It was important to design the software architecture and software components correctly at the start to avoid costly revisions.
- It was challenging to convince researchers to deposit their data, due to a perceived notion that the database is a redundant platform.

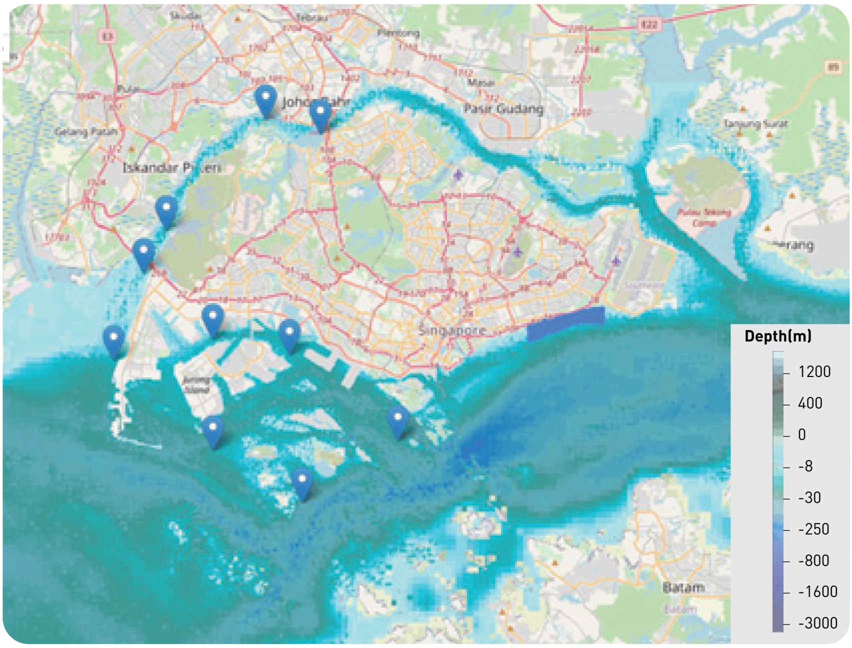


Figure 1: METIS map feature.

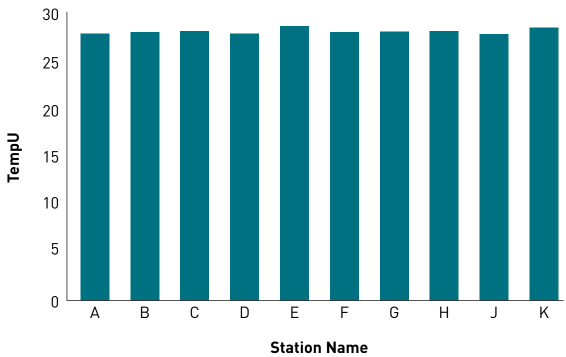


Figure 2: METIS data visualisation feature.

Future directions

METIS should be seen as a precursor to a national-level data-sharing initiative for research purposes, which will foster better and improved collaboration for future marine research projects. Nationalising METIS or a METIS-like database and a data platform will greatly help to realise the value of accessible cross-disciplinary marine science data analytics for Singapore. A centralised multi-featured web portal for this facilitates a 'one-stop shop' for researchers, institutions, and agencies to discover and retrieve such data.

At the time of writing, we are reviewing the feasibility of integrating METIS' data into NRF's Marine Environment Sensing Network (MESN) project, which kicked off in October 2020. In the MESN project, a data platform will be built to house data from sensors on three buoys, to be located at St. John's Island, Raffles Lighthouse, and Pulau Ubin. Potentially, MESN's data platform can also be linked to GeoSpace-Sea, Singapore's National Marine Spatial Data Infrastructure—such that users may access marine data from both these platforms.

P12

MICROBIALLY INFLUENCED CORROSION

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Introduction

Microorganisms and biofilms that colonise metal structures affect physicochemical interactions at the metal/liquid interface, either slowing down or accelerating abiotic corrosion processes. The metal deterioration phenomena related to the presence of microorganisms are termed microbially-influenced corrosion (MIC). The effects of MIC are similar to those observed in other types of aqueous electrochemical corrosion and contribute to approximately 20% of the observed material degradation associated with corrosion. Microorganisms play an important role in the long-term corrosion process, and understanding this is key to developing modelling techniques to determine the operational lifetime of marine infrastructures, which is critical to managing risk for key industrial assets in marine settings.

The corrosion process has been well studied at ambient pressure conditions, representing surface and shallow-water environments. However, increasingly, oil and gas infrastructure is being installed in the deep ocean, where the environmental conditions are characterised by extremes of temperature, salinity, and significantly, high hydrostatic pressure (HHP). Few studies have attempted to characterise MIC under these environmentally relevant conditions.

Main findings

We have developed a world-first, high-pressure incubation chamber that incorporates electrodes to allow real-time monitoring of corrosion potential as microbes attach to and grow on metal surfaces at pressures relevant to the deep sea. A technology disclosure has been filed for this system. Using our incubation chamber, we have shown that the redox potential of key respiratory elements that *Shewanella oneidensis* uses to perform extracellular electron transfer is affected by pressure. We also observed that cell growth is affected by pressure, with the most growth at 20 MPa and slightly less at 30 MPa. This does not correlate directly with the observed changes in cytochrome and flavin function. These findings highlight that the electrochemical environment experienced by microorganisms may differ significantly across depths.

The team was able to show there was a correlation between areas where biofilms form on metal surfaces and changes in surface corrosion. This led the team to explore the surface microstructure to further link sites of corrosion to biofilm formation. Growth at elevated hydrostatic pressure was shown to shift the population from the planktonic phase to biofilm growth.

The team participated in a number of sampling campaigns to collect microbial communities that would be relevant for deep-sea corrosion. The first was from Israel in June 2018 from a depth of 1,500m. We also obtained samples from Japan in November 2018 at 1,000, 2,000, and 5,000m by remote-operated vehicle (ROV) in the East China Sea (Okinawa Trough). These samples, which included sediment and water samples, have been enriched in laboratory high-pressure reactors and are currently being investigated as part of the programme. We also recovered, as part of these samples, steel chain links that had been laid down in the sediment at 2,000m depth for 10 years. These are being analysed in the laboratory to characterise the corrosion and microbial communities associated with those. The third was a research cruise to the Clarion-Clipperton Zone in the Eastern Pacific Ocean to collect materials from polymetallic nodules.

Future directions

The project team has secured funding through the Competitive Research Programme (CRP), which will ensure that the expertise, equipment, and resources (e.g., deep-sea cultures) continue to provide invaluable discoveries about how microbes influence corrosion in the deep ocean. The team has additionally made closer collaborations with Exxon-Mobil and Keppel Offshore & Marine to further support the project and to provide direct impact for industrial partners. We will continue to seek further partnerships with other researchers in the field as well as try to expand on those industrial collaborations to bring additional value to the work started here, under MSRDP-P12. The overall goals will extend the findings from the MSRDP programme, with a focus on the role of microbial communities in mediating corrosion, to develop metabolic models that will be used to create hypotheses around the specific mechanisms of corrosion, to develop and implement genetic tools to test hypotheses around the roles of specific genes or pathways in corrosion, to exploit these discoveries to make better predictive MIC models and corrosion sensors, and to explore mitigation strategies for MIC.

→ A researcher examines the extent of corrosion that is influenced by microbes.

P15

GENOMIC AND METABOLOMIC APPROACH TO THE DISCOVERY OF FUNCTIONAL METABOLITES FROM MARINE MICROBES

Lik Tong Tan (PI)[1], Zhao-Xun Liang (Co-I)[2], Christina Chai (Co-I)[3], Koh Siang Tan (Co-I)[4,5]

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Introduction

Singapore's strategic position on the edge of the Coral Triangle, between the Pacific and Indian Oceans, presents valuable access to rich marine bio-resources. Previous attempts at bioprospecting have been difficult as organisms in the tropics tend to be diverse but low in abundance. As such, the traditional 'grind and find' strategy of natural product research has not been robust, and few significant discoveries have been made. Technological advances over the past decade, particularly in the genomic and analytical arena, have opened new opportunities, and the race to secure useful marine products is back with a vengeance. The overall research aim of this project is to uncover novel functional metabolites from marine microbes associated with diverse marine samples, including corals, sponges, and sediments, using an integrated approach of genomic mining, and chemical and biological screening.

Main findings

Of a total of 333 marine bacterial strains isolated from various marine samples using a culture-dependent method, 40 microbial strains (12%) were found to possess significant quorum sensing inhibitory activity in a dose-dependent manner based on the *P. aeruginosa* biosensor strains. The genomic annotation of selected marine bacterial strains was performed using antiSMASH, and revealed unique natural product biosynthetic gene clusters related to non-ribosomal peptide-synthetase (NRPS) and terpenoid gene clusters. Moreover, the mass spectrometry-based metabolomic profile based on molecular networking revealed that the chemistry of the bioactive fractions from these microbial strains is diverse and complex (Figure 1).

In addition to marine bacteria, about 41 fractions/extracts derived from various marine cyanobacterial strains were screened for biological activity. A high percentage (about 68%) show significant quorum sensing inhibition and/or brine shrimp toxicity. Chemical investigation, including mass spectrometric molecular networking, of the marine cyanobacterium *Symploca hydnoides* revealed that it is a prolific source of new functional molecules. Subsequent isolation and purification led to the report of novel classes of cyclic peptides/depsipeptides, including trikoramides, trikorveramides, and trikorastatins (Figure 2). The major compound, trikoramide A, was shown to possess significant anticancer activity against MOLT-4 and AML-2 cancer cell lines.

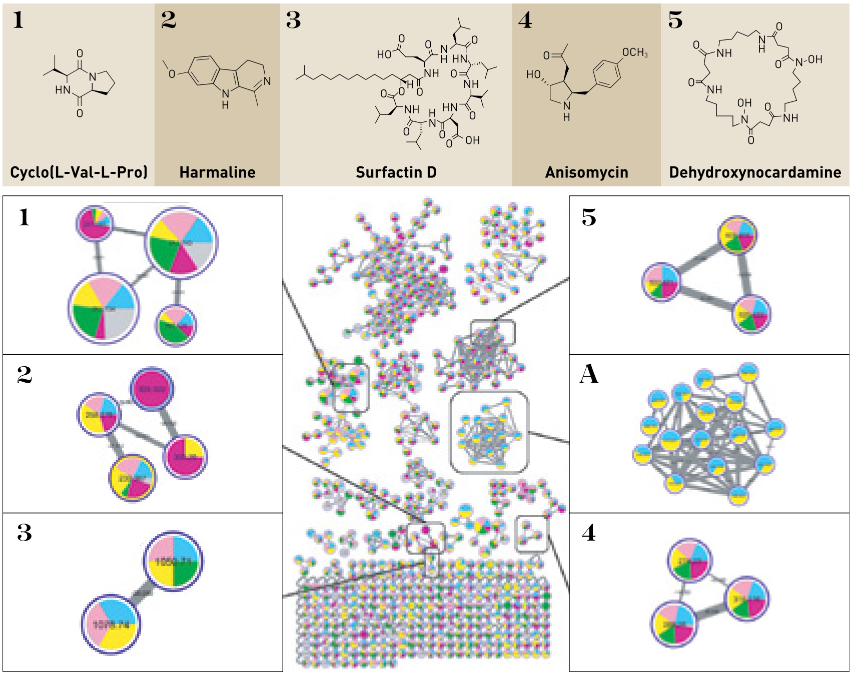

Figure 1: Annotation of molecular networks of 591 parent ions detected in extracts of five sponge-derived marine bacterial strains that showed anti-quorum sensing activity.

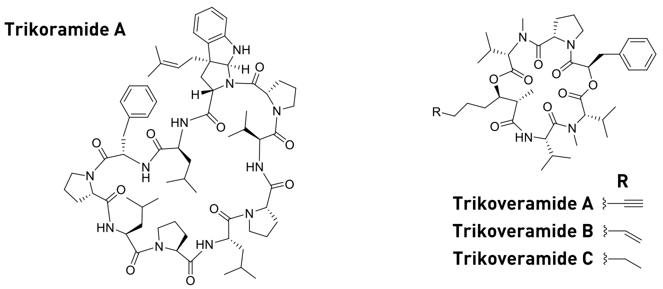

Figure 2: Novel bioactive compounds from the marine cyanobacterium *Symploca hydnoides*.

Future directions

This project resulted in the discovery of numerous microbes with unique chemistry and related biosynthetic gene clusters. Future directions include:

- Large-scale fermentation of selected marine bacterial strains for isolation and purification of functional molecules.
- Mode-of-action and structure–activity relationship studies of selected cytotoxic marine microbial compounds.
- Genome mining of useful enzymes employed for the biosynthesis of novel bioactive natural products.

P20

PASSIVE ACOUSTIC MONITORING OF CORAL REEF ECOSYSTEM HEALTH

Mandar Chitre (PI)

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Introduction

Coral reefs are like rainforests of the sea, supporting 25% of all marine biodiversity on the planet. Climate change, pollution, poor fishing practices, and destructive coastal developments have destroyed more than 60% of the reefs worldwide. Singapore as a major global maritime hub is not spared. We have lost up to 65% of live coral cover since 1986, hence safeguarding our coral reefs is of utmost importance.

Existing monitoring methods rely mainly on visual surveys, either through direct diver observations or video surveys. These methods are labour intensive, expensive, and especially difficult to perform in the turbid waters around Singapore. When safe-distancing measures were implemented during the COVID-19 pandemic, marine scientists who usually carry out routine surveys were suddenly land bound and unable to monitor the coral reefs. This further increased the urgency of harnessing technology for coral reef monitoring. One possible approach is to listen to the coral reef soundscapes using underwater passive acoustic recorders.

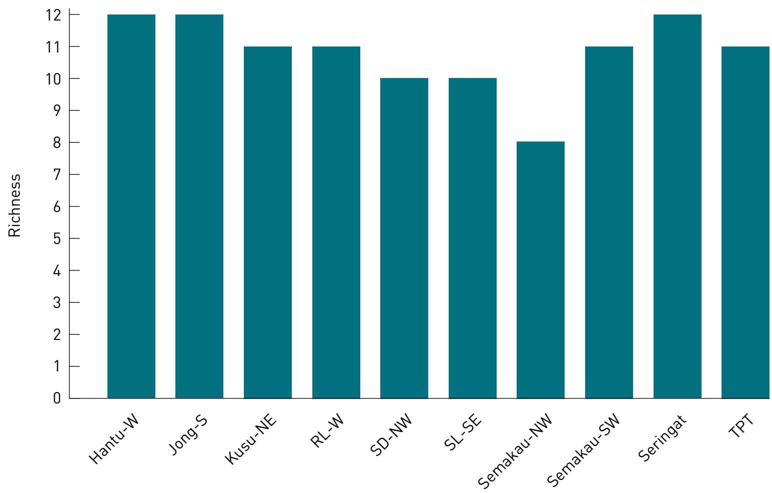
In this project, we studied coral reef soundscapes and developed techniques for passive acoustic monitoring of coral reef ecosystem health. To understand the relationship between soundscapes and reef health, we collected long-term acoustic data from 10 reef sites in Singapore's waters, and at the same time, conducted a standard visual survey of these reefs. We then extracted useful parameters from the data and developed a model of the relationships between the acoustic parameters and reef health. The techniques developed here can be used to supplement visual surveys to allow more continuous and spatially dense reef monitoring, at a fraction of the cost of diver observations.

Main findings

Diversity in biological sounds indicates thriving species and a healthier coral reef ecosystem. Given a continuous long-term acoustic recording at a reef site, different sounds can be extracted by first detecting individual sounds and then clustering these into coherent groups. Manually inspecting the resultant small groups enabled us to select those that originated from biological activities. However, in Singapore waters, these sporadic biological sounds are often drowned out by the ubiquitous snapping shrimp noise and ship noise. The problem is further complicated by the enormous scale of the data collected in long-term passive acoustic monitoring. To resolve this, we developed time- and memory-efficient methods to discover repeated sounds from the coral reef soundscapes.

From these acoustic recordings, about 1.4 million episodic signals were identified using robust signal detectors. Contrastive learning with density-based clustering followed by manual reassignment was employed to provide end-to-end representation learning for the acoustic data. This method reduces the dimension of raw sound snippets from a sample size of several thousand to tens. At the same time, this method preserves distinct information of different types of sound. Using this method, we identified several tens of unique common sounds. Figure 1 shows the number of unique, commonly occurring sounds of biological origin, denoted by *richness*, at different reef sites in Singapore. For example, preliminary analysis of our recordings from Pulau Hantu West (Hantu-W), Pulau Jong South (Jong-S), and Pulau Seringat (Seringat) show approximately 30% more sound richness than at Pulau Semakau Northwest (Semakau-NW), probably as a result of having more biodiverse ecosystems.

Figure 1: Number of unique, commonly occurring sounds of biological origin, denoted by *richness*, at different reef sites in Singapore.



Future directions

In this project, we assembled passive acoustic recorders and deployed them for data collection. Each recorder is equipped with a hydrophone and environmental sensors. We conducted deployments at reef sites in Singapore's waters over the course of two years. The acoustic data contains various sounds generated by marine organisms (snapping shrimp, marine mammals, etc.), natural physical events (wave, rain, etc.), and human activities (shipping, divers, etc.). Being able to detect and classify different types of sound, we can have a better understanding of the impact of human activities on the reef health, and hence propose methods to mitigate noise pollution in coral reefs. For example, we can possibly identify which soniferous animals are most vulnerable to a specific type of man-made noise by comparing the occurrence of these sounds in our recordings. The data spanning over pre- and post-COVID Circuit Breaker could be valuable to study the impact of the COVID-related short-term decline in human activities on soundscapes in Singapore's waters.

P21

TOWARDS THE DESIGN AND DEVELOPMENT OF A PROTOTYPE DEVICE FOR REAL-TIME MONITORING OF ALGAL TOXINS

via biomimetic chemical sensors

Christina Chai (PI)[1], Yen Wah Tong (Co-I)[2], Saif Khan (Co-I)[2], Sandric CY Leong (Co-I)[3,4]

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Introduction

Harmful algal blooms (HABs) refer to any algal blooms that result in undesired consequences, such as eutrophication and the poisoning of marine organisms including fish. In the recent decade, the global incidence of HABs from toxic phytoplankton species has increased both in frequency and distribution. A major threat associated with HABs are phycotoxins produced by dinoflagellates that can accumulate in marine organisms (e.g., shellfish) that are then consumed by humans—leading to human toxic syndromes and even death in some cases. There are also associated environmental and economic problems that could arise as a result of the poisoning of marine organisms.

During periods of algal blooms, both food and water sources for humans may be affected. For instance, toxins produced by HABs may contaminate drinking water. This can arise from desalination processes that have become inefficient under conditions of severe algal blooms. Mitigation strategies developed to combat these problems are placed in order to reduce health and economic risks, but are often reactive rather than predictive. Two matters are critical in mitigation strategies: to be able to detect the phycotoxins quickly and to be able to reduce or remove the phycotoxins from affected waters. Although methods already exist for the detection of algal toxins, these approaches rely on sampling of water followed by analysis, which takes time and causes delay in mitigation responses. Ideally, real-time monitoring of algal toxins of interest is needed to assess the severity of algal blooms as well as to enable tracking of environmental and climatic parameters to episodes of severe algal blooms. In addition, real-time monitoring has a greater likelihood of being able to provide early warning information on developing toxic conditions in susceptible waters. This provides a response time for relevant stakeholders. A commonly found HAB toxin in Singapore is domoic acid (DA), which is the causative toxin responsible for amnesic shellfish poisoning (ASP). In view of the relevance of DA both in Singapore's waters and worldwide, our research aims to develop detection systems for domoic acid in a proof-of-concept study. The detection of other algal toxins of interest can, in principle, be carried out using a similar approach.

Main findings

Our approach is to synthesise specially designed molecularly imprinted polymers (MIP) that will specifically recognise DA and bind to the MIP. To harness the potential of MIPs in producing practical field devices, their binding capabilities should be coupled to systems that can generate a measurable and concentration-dependent output. The detection method has to be highly sensitive as the concentrations of DA to be detected in the field are likely to be in the parts-per-billion range. In view of the toxicities of DA and the limited supply of DA commercially, one key aspect of this project was to identify surrogates of DA that can be used as templates in the synthesis of MIPs.

From our studies, we designed and synthesised a number of DA surrogates and assessed these as templates for molecular imprinting. Our studies identified suitable templates that were used to synthesise MIPs that in turn showed strong binding to DA. With these templates in hand, we examined possible sensitive reporter systems to detect the binding of DA onto the MIPs. Two methods were examined. The first employed MIP-quantum dots that would generate a phosphorescence signal upon binding of the analyte, while the second method utilised an electrochemical readout as a means of determining binding of DA to MIPs.

We found that our MIP-quantum dots were sensitive to low concentrations of domoic acid in water, but could not reliably detect the analyte in seawater. In addition, the synthesis of the MIP-quantum dots was highly sensitive to the conditions for its fabrication and is not scalable. Our preliminary studies using electrochemistry as a detection method showed promising results but further optimisation is needed.

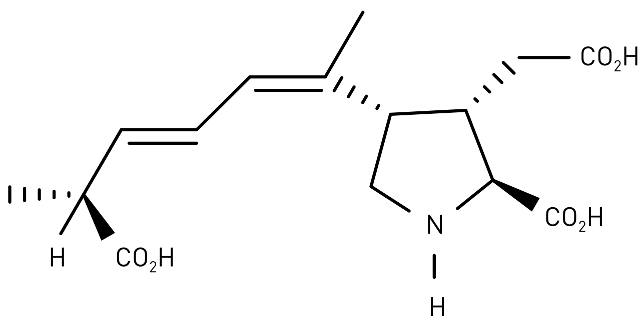

Figure 1: Domoic acid.

Future directions

Our studies have identified surrogates of domoic acid that can be used as templates in MIP synthesis. However to date, we have only evaluated two reporter systems, of which limitations have been identified. Future work can focus on the optimisation of these systems to improve sensitivity, compatibility in seawater, reproducibility, and device fabrication. In addition, alternative reporter systems can also be investigated—for example, methods that lead to fluorescence signals are likely to be highly sensitive.

P28

EFFECT OF STRAIN-ENGINEERED SUPERHYDROPHOBICITY ON ADHESION OF MARINE ORGANISMS

Ping Wu (PI)

Singapore University of Technology and Design

Introduction

Its advantageous geographical position has enabled Singapore to grow its maritime economy and become the world's busiest port. Many oceanic vessels transverse a great distance and use Singapore's port for maintenance and supply replenishment. Because many marine organisms must attach to surfaces, it is a common sight to see the hulls of vessels overgrown with a plethora of marine species. Their presence substantially increases the drag of ships in the water while travelling, which raises fuel consumption. Removing these fouling organisms is troublesome and costly.

The adhesive behaviour of fouling organisms is due to their preferential attraction towards hydrophilic surfaces, for instance, metallic surfaces, which are commonly used for vessel hulls. Although engineered chemical coatings are available to prevent fouling, these coatings are (1) costly to apply, (2) subject to delamination over time, and (3) toxic. In spite of worldwide R&D efforts to produce cheaper, more durable, and environmentally friendlier chemical antifouling alternatives, there are no commercially feasible solutions yet. This research project aimed to explore a nonchemical solution for marine antifouling applications.

Main findings

We marshalled the fundamentals of material mechanics, chemistry, and thermodynamics to develop a new method to modulate the surface hydrophobicity of metallic surfaces by applying an easy implementable mechanical straining. It was observed that when a metallic surface—in this case stainless steel 304L and aluminium 5083—was mechanically strained, its surface hydrophobicity increased permanently, a result of both elastic and plastic deformation. This unique change in surface wettability was due to the formation of more ordered microstructures (i.e., a reduction in surface entropy) compared to the surface of the bulk metals. Further tests supported the advantages of applying this technique; this is shown in Figure 1, in the lower right images, of an unstrained (left inset) and a strained-unstrained patterned surface. Currently, this method is pending for patent filing.

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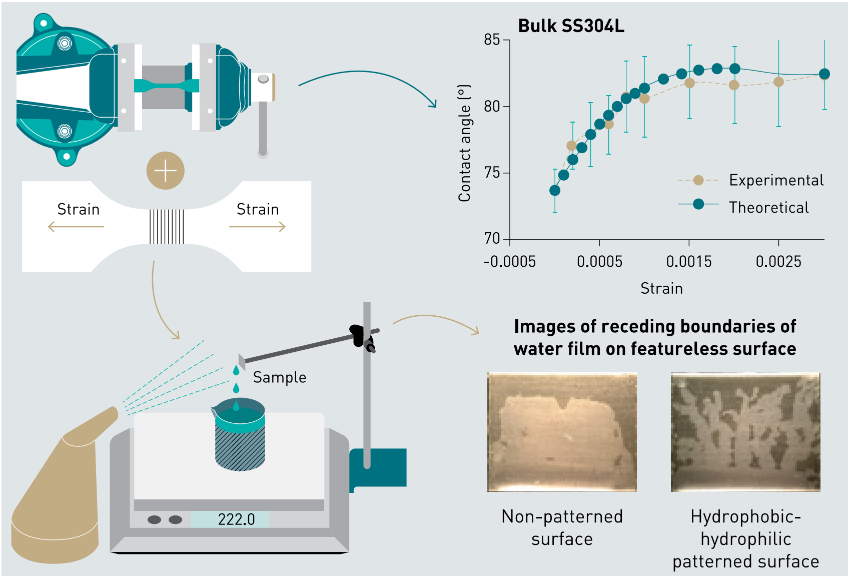
Figure 1: A new method to modulate the surface hydrophobicity of metallic surfaces.



In our tests, this newly developed approach increases the surface hydrophobicity of a vessel hull, and discourages adhesion of sea creatures to the strained surfaces, as demonstrated in Figure 2 using mussel *Mytella strigata* as a representative of marine fouling organisms. The effect is shown by the numbers of byssal threads produced by the mussel on each type of surface.

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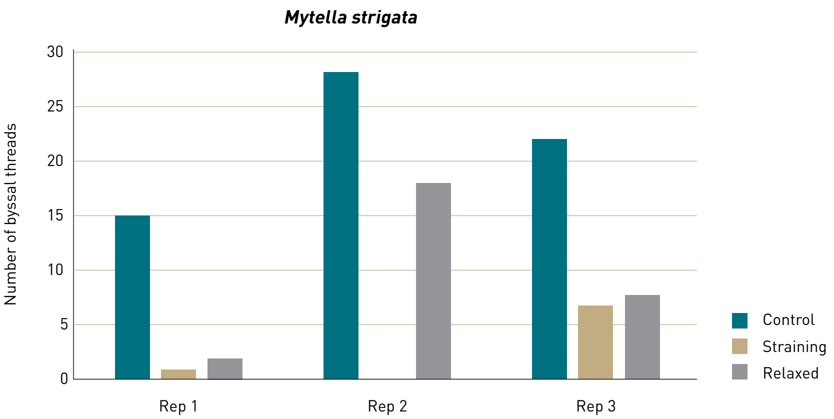
Figure 2: Numbers of byssal threads produced by *Mytella strigata* on each type of surface.



Future directions

We aim to apply the developed strain hydrophobicity principles to design and fabricate antibacterial and biodegradable medical devices; industrial collaborations to this effect are still ongoing. Further funding could also be used to apply the entropic straining principles to study and design dielectric materials and devices, or to use the entropic wetting principles to design and fabricate CO_2 capture devices for coral reef settlements.

P29

BIOINSPIRED LIQUID INFUSED COATINGS TO PREVENT MARINE BIOFOULING IN THE TROPICAL ENVIRONMENT

Ali Miserez (PI)[1], Scott Rice (Co-I)[2]

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Introduction

The firm adhesion of marine organisms on sea-immersed structures such as shipping vessels, port and aquaculture infrastructures, or oceanographic sensors is known as marine biofouling, and has serious economic and environmental consequences. Worldwide, it is estimated that the economic cost of biofouling on shipping alone is US$30 billion per annum. Further negative outcomes of additional fuel consumption due to marine biofouling are increasing greenhouse gas emissions that contribute to climate change. In addition, hard foulers such as barnacles and mussels can severely damage pipelines in coastal power plants, reduce heat exchange efficiency, or even clog water distribution pipelines. Singapore is particularly prone to biofouling, and thus, ideally suited to conduct biofouling research due to: (1) the warm tropical water conditions allowing year-round testing; (2) the presence of a wide range of fouling organisms with a high spatial density; and (3) it is a major shipping centre that further aggravates fouling stresses, such as the translocation of invasive species.

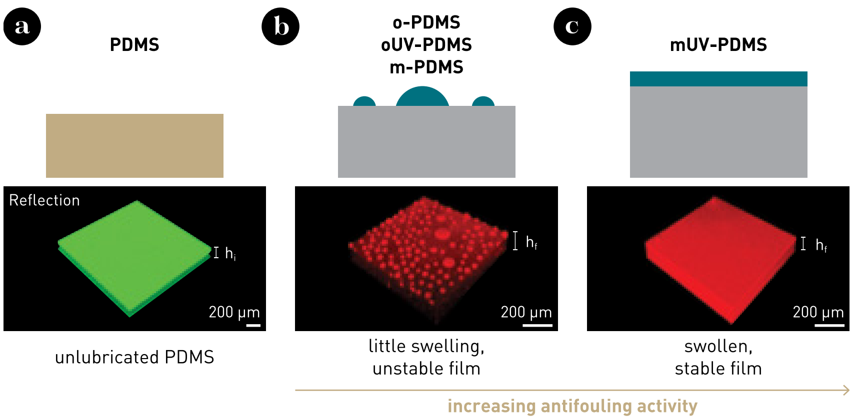


Figure 1: Schematic and confocal microscopy images of SLIPS surfaces infused with various biolubricants. (a) Unlubricated PDMS gel. (b) PDMS gel infused with oleic acid (o-PDMS) or methyl oleate (m-PDMS), or UV-treated PDMS infused with oleic acid (oUV-PDMS). (c) PDMS gel infused with methyl oleate (mUV-PDMS). Reproduced from Basu et al., J. Coll. Inter. Sci. 568. 185-197, 2020.

Slippery Liquid-Infused Porous Surfaces (SLIPS) have emerged as a very promising class of repellent coatings with excellent anti-marine biofouling characteristics. In this technology, a porous substrate (for example, a polymeric gel) is infused with a low-surface energy fluid usually made of a silicon oil, which remains entrapped within the porous substrate owing to the strong chemical affinity between substrate and lubricant.

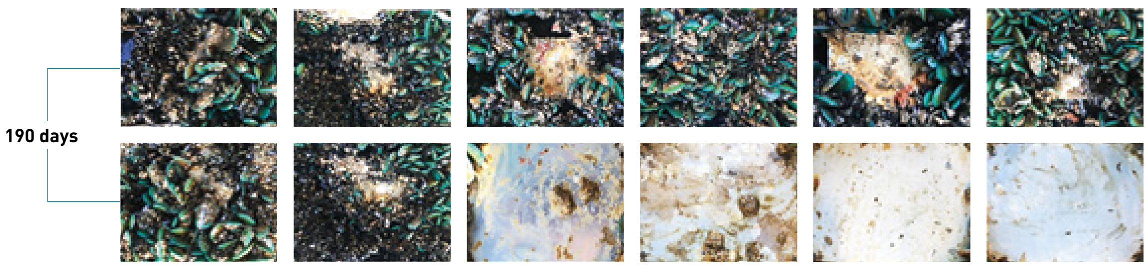
This project had two main directions. First, commercially available synthetic oils/lubricants for SLIPS are usually fluorinated and their slow leakage over time is a matter of concern from an environmental perspective. Thus, we aimed to develop fully eco-friendly versions of SLIPS surfaces by replacing the silicon-based lubricant with bio-based lubricants, and to demonstrate that these coatings can deter biofouling and are safe for the marine environment. Second, we aimed to investigate the resistance against marine biofouling of a range of biocide-free SLIPS coatings recently developed by our commercial partner on this project—Adaptive Surface Technologies (AST) in Cambridge, Massachusetts, USA—notably in the aggressive biofouling environment of Singapore.

Main findings

We have developed SLIPS coatings using bio-based lubricants as infusing phases, namely oleic acid (OA) and methyl oleate (MO). The infusion efficiency was verified with confocal microscopy, surface spectroscopy, wetting efficiency, and nanocontact mechanics. Using green mussels as a model organism, we have found that UV-treated Polydimethylsiloxane (PDMS) infused with MO gave the most uniform infused film (Figure 1), in agreement with the lowest interfacial energy among all surface/biolubricants produced. These surfaces exhibited excellent antifouling properties in the lab, as defined by the lowest number of mussel adhesive threads attached to the surface as well as by the smallest surface/thread adhesion strength. We found a direct correlation between antifouling performance and the substrate/biolubricant interfacial energy.

The fouling resistance performance of our industrial partner's coatings was evaluated both in the lab and in the field, by conducting multi-month immersion tests in high-fouling pressure environments. In the lab, we showed that the coatings were largely able to deter settlement of marine mussels, one of the most invasive marine biofouling organisms, and to weaken their adhesion strength. The key design parameter of slippery coatings to minimise fouling is the thickness of the entrapped lubricant overlayer, which was assessed through depth-sensing nanoindentation measurements. We found that the surface energy (i.e., hydrophobic versus hydrophilic), on the other hand, did not significantly affect the antifouling performance of these coatings. After immersion in the field in stagnant waters, all coatings exhibited efficient foul-release capacity against macrofoulers, whereas under stronger hydrodynamic flow conditions, only weakly attached biofilms were detected with a bacterial community composition that was independent of the surface energy.

Figure 2: Biofouling results of the field study carried out in stagnant water conditions in a mussel aquaculture farm. Four SLIPS coatings (iPDMS, SM, SC, and SN) were evaluated as well as two control samples (Primer 300, Tie-coat 731) for 190 days. The images are before (top) and after (bottom) manual cleaning. On the SLIPS coatings, mussels were readily removed from the coatings by applying minimum manual force, whereas on the control coatings, firm attachment completely prevented removal of the biofouling communities manually. Reproduced from Basu et al., J. ACS Applied Polymer Materials, 2 (11), 5147-5162, 2020.



P30

BIODIVERSITY AND BIOPROSPECTING OF MAGNETOTACTIC BACTERIA:

An overlooked biotechnological resource in the tropical marine environment of Singapore

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Introduction

Magnetotactic bacteria (MTB) can produce magnetic nanoparticles in an organelle called the magnetosome, and their motility can be directed by the earth's geomagnetic or externally applied magnetic fields. MTB and MTB-derived magnetic nanoparticles are effective bioagents for magnetic resonance imaging of tumours, magnetic hyperthermia for cancer therapy, targeted drug delivery, and to detect nucleotide polymorphisms to diagnose diseases such as cancer, hypertension, and diabetes. Hence, MTB have attracted much research attention in biotechnology, biomedicine, and advanced materials science.

The tropical water temperatures around Singapore (27–31°C) provide a unique opportunity for bioprospecting of MTB that have optimum growth under typical biotechnological laboratory conditions. The diversity of MTB in equatorial Asia, which has near-zero geomagnetic inclination and a weak magnetic field, has never been explored. This study aimed to decipher the diversity of marine MTB in Singapore to facilitate MTB bioprospecting for biotechnology.

Main findings

Metagenomic sequencing and bioinformatic analyses were performed on the DNA directly extracted from sediment/water slurries collected from Johor Strait to reveal the biodiversity of marine MTB in Singapore. Key findings include:

(1) Most of the MTB in Singapore represent novel MTB taxa that cannot be classified to species level;

(2) The relative abundance of MTB (~0.2–1.69%) in Singapore was found to be substantially lower than studies for other regions;

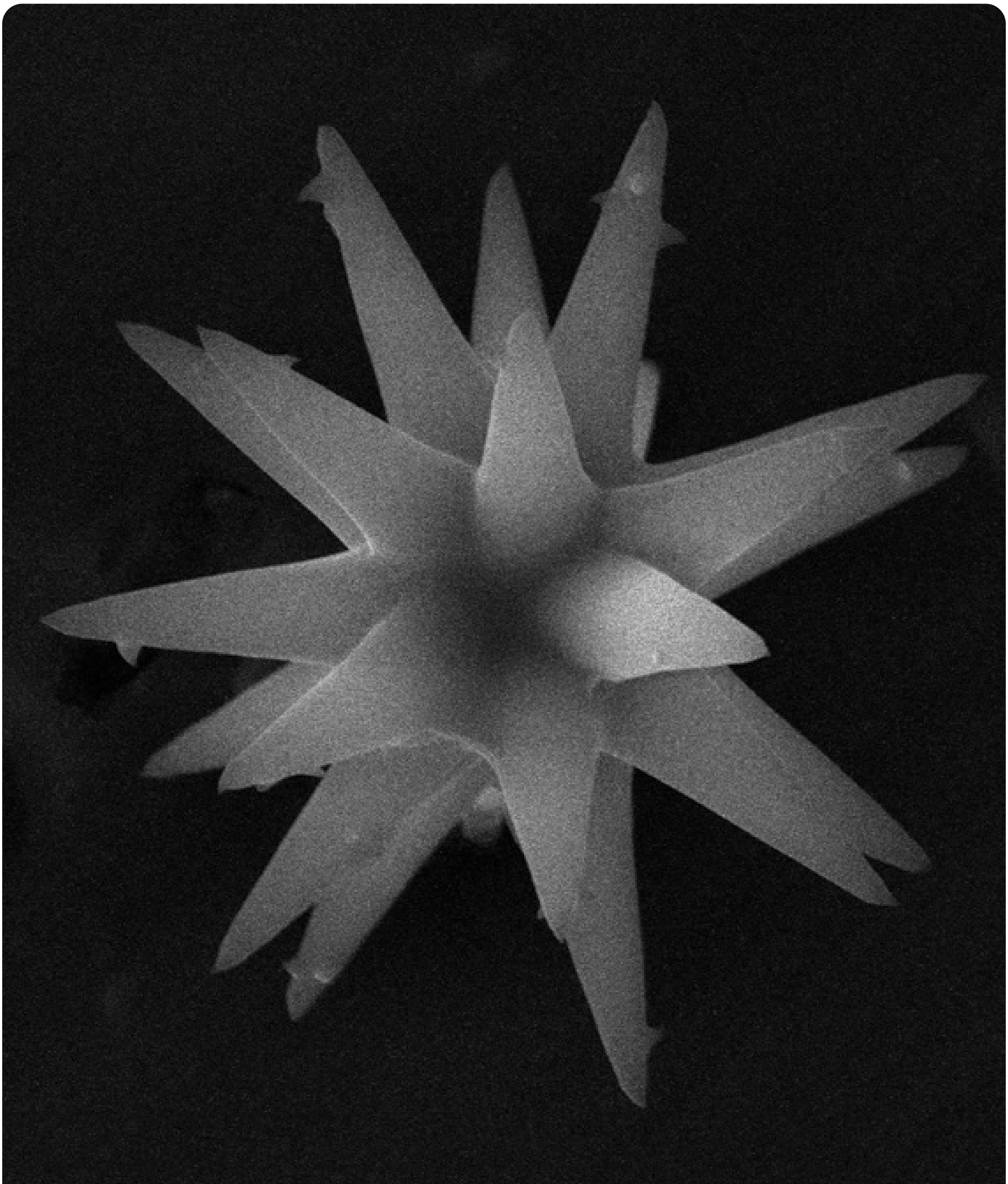
(3) The genera *Magnetovibrio* and *Desulfamplus*, but not *Magnetococcus*, were the dominant MTB in Singapore; and

(4) Three MTB genomic bins were recovered and they are unclassified at the species level, with *Magnetovibrio blakemorei* being the closest-associated genome.

This study fills in a knowledge gap by revealing novel MTB biodiversity in a tropical environment near the geo-equator.

Future directions

Further work is needed to unravel the ecological roles of marine MTB in the tropics, as well as to bioprospect novel MTB that have been adapted to tropical marine environments for biotechnological applications.



Scanning electron microscope image of a Spheraster at 6000x magnification

P34

DISCOVERY OF ANTIMICROBIALS FROM MARINE MICROALGAE FOR BIOFILM INFECTION CONTROL

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Introduction

Bioprospecting marine organisms for bioactive natural products is a well-established practice that has uncovered novel drugs for use in medical and antimicrobial applications. The present research is built on evidence that pathogens involved in chronic bacterial infections, such as *Pseudomonas aeruginosa*, live as biofilms. Three key factors are known to induce bacterial biofilm formation, namely quorum sensing, the molecule bis-(3'-5')-cyclic diguanosine monophosphate (c-di-GMP), and small RNA molecules. In particular, the use of small organic molecules that interfere with bacterial quorum sensing represent an alternative approach in treating pathogenic infections.

Many marine organisms successfully defend themselves against microfouling (biofilm formation) by the production of secondary metabolites. Similarly, the surfaces of most marine benthic macroorganisms and microbial prokaryotes, such as sponges and cyanobacteria, are devoid of fouling, indicating that these organisms might produce compounds to prevent microfouling. The primary objective of this research project is to screen marine organisms, such as microalgae, bacteria, and sponges, for potential anti-infective compounds that exhibit completely new modes of action to disrupt bacterial biofilm formation via inhibition of quorum sensing systems in *P. aeruginosa*.

Main findings

More than 80 extracts/fractions derived from various filamentous marine cyanobacterial strains and sponge species were screened for quorum sensing inhibitory (QSI) activity. Of these, at least 40 fractions/extracts exhibited QSI activity, and a number of compounds were subsequently purified and their structures determined. For instance, a series of novel cyclic peptides, known as the trikoramides, possessed significant QSI activity. Trikoramide D (Figure 1), in particular, showed a dose-dependent response in the QSI assay based on *P. aeruginosa lasB-gfp* and *rhlA-gfp* biosensor strains.

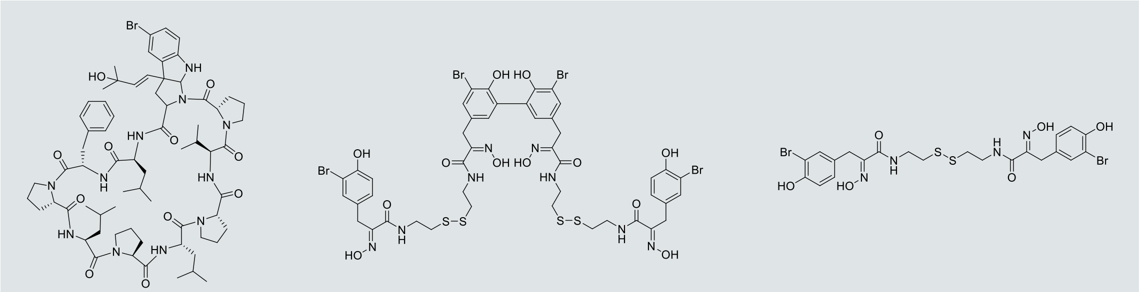


Figure 1: Selection of marine-derived compounds with significant QSI activity.

In addition, sponge-derived molecules, such as psammaplin A and bisaprasin (Figure 1), revealed exceptional QSI activity. These compounds were shown to inhibit the production of the enzyme elastase, in a phenotypic elastase assay when tested at 50 µM. Moreover, from mass spectrometric-based molecular networking analysis, structurally novel compounds were detected from marine-derived fractions with significant QSI activity. This is illustrated by five QSI active fractions derived from the cyanobacterium *Symploca* sp., where 899 ions were detected in the molecular networking clusters (Figure 2).

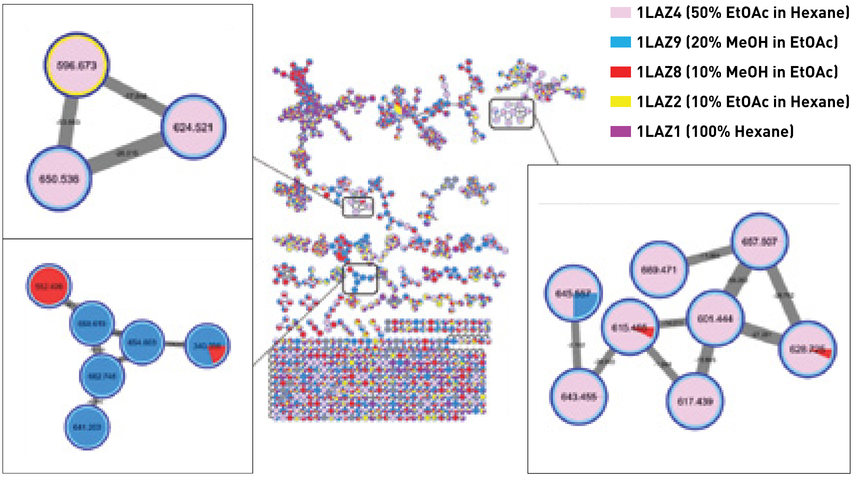


Figure 2: Molecular networking clusters of 899 parent ions from five QSI active fractions from *Symploca* sp.

Future directions

This project resulted in the discovery of new structural classes of compounds having quorum sensing inhibitory activities. Future directions include:

(1) Further biological evaluation of QSI active compounds in preventing biofilm formation in P. aeruginosa as well as their regulation of gene expression based on transcriptomic studies.

(2) Mode of action and structure-activity relationship (SAR) studies of QSI active compounds.

(3) In vivo assay of bioactive compounds in mouse model to assess their ability to prevent bacterial infection. This could include testing with known antibiotics in combination therapy strategy in combating bacterial infections.

P46

AN ENHANCED BATHYMETRY FOR OCEANOGRAPHIC RESEARCH AND APPLICATIONS

Seng Keat Ooi (PI)

Tropical Marine Science Institute, National University of Singapore

Introduction

Presently in Singapore, a unified set of data that encompasses the intertidal region is still lacking. Part of the issue is a near-absence of data in the intertidal region. This project focuses on developing a methodology to obtain intertidal bathymetry data for Singapore by merging various sets of data and creating one unified bathymetric data set. Creating this set of data, which does not exist at the present moment, could provide Singapore bathymetry data for coastal and marine science research, and applications including adaptation to sea-level rise.

In creating this unified data, a tool will be developed to aid in the stitching or merging of data sets where there are gaps between high resolution topographic/bathymetric sets and low resolution, or alternative methods of data collection. This is particularly useful in areas where there are natural slopes rather than hard structures, which have pre-defined shapes and are simple to interpolate or merge. An application will also be demonstrated to show the usefulness of having such a set in considering wake/wave run-up on a part of Singapore's coastline.

Main findings

Within this project, we trialled various methods to create a high resolution data set to fill a relatively large gap between two sets of provided high resolution data. Some of the conventional geographical interpolation schemes were tested here, including methods like: Kriging, Inverse Distance Weighting (IDW), Global Polynomial Interpolation (GPI), and Local Polynomial Interpolation (LPI), all of which are found in geographical information systems software (GIS) like QGIS and ArcGIS.

Of these, GPI gave the best performance, when measured by the root mean square error (RMSE) from known observed values. It was then found that coupling GPI with an artificial neural network (ANN) scheme, the latter developed in-house, managed to improve the interpolation performance.

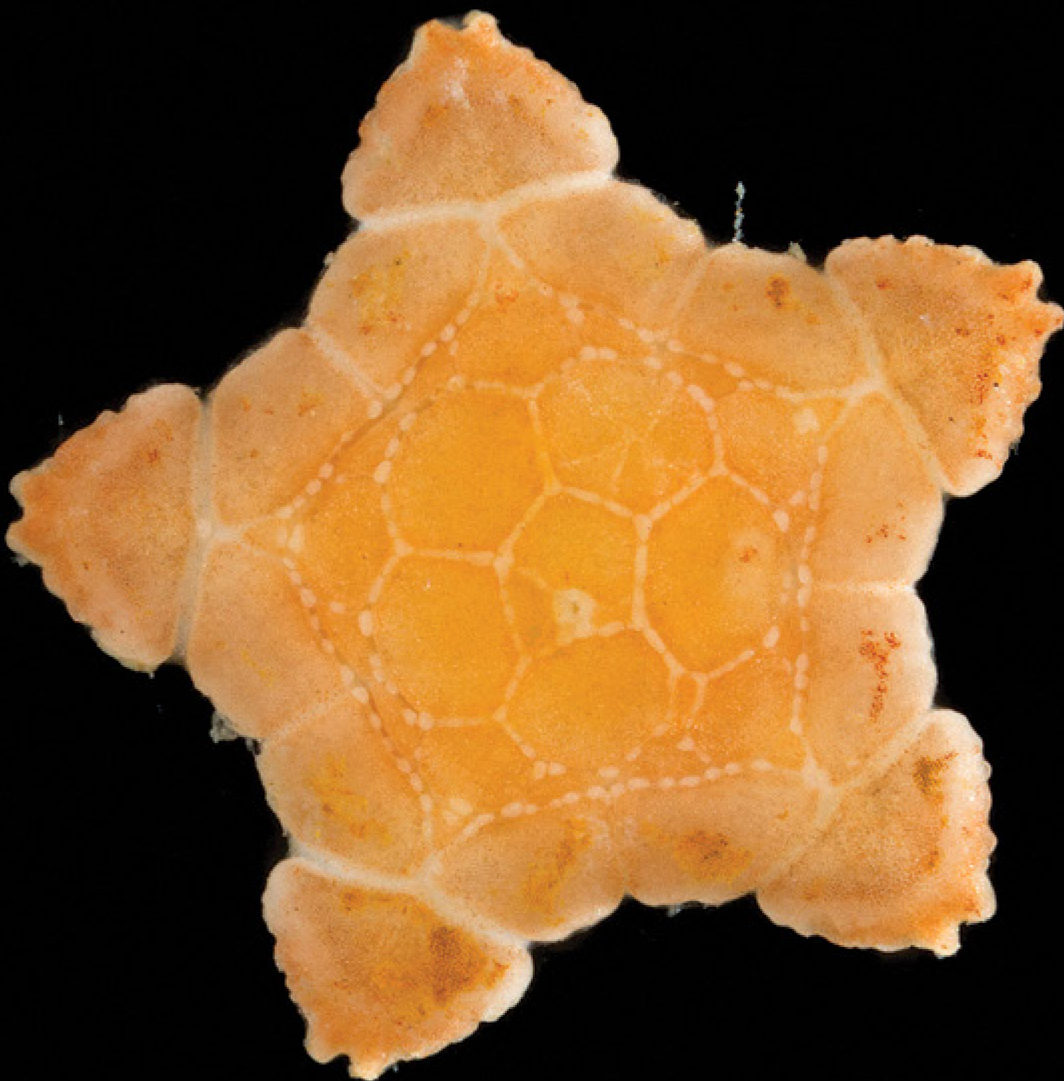
Based on the findings, we have implemented a proof-of-concept (POC) ANN software algorithm for creating an integrated intertidal bathymetry/topography data set. We further implemented a POC map interface to view and export unified bathymetry/topography data.

Low tide at St. John's Island lagoon

Future directions

This project established important collaborations with Singapore's Maritime and Port Authority (MPA), which kindly provided us with the essential topography and bathymetry data sets.

Through this project, there was a realisation that more data would be required in the gap areas to validate the interpolation tool better and across different types of topography/bathymetry. As such, the team has sought and secured a Cities of Tomorrow (CoT) grant to obtain data efficiently in the intertidal regions around Singapore.


A tiny unidentified sea-star collected from Singapore

Project Summaries

OTHER INITIATIVES

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EXPLORE:

Marine science student research grants

Serena Teo (PI)[1,2], Lik Tong Tan (Co-I)[3]

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Introduction

The Explore research grants aim to provide research support (up to six months) for undergraduate/diploma/junior college level students (17 to 25 years old), to undertake exploratory marine science research at St. John's Island National Marine Laboratory. The objectives of this student programme are:

- Encourage exploratory research relevant to the domains of the MSRDP,
- Nurture multidisciplinary problem-solving skills and interest in STEM subjects,
- And encourage interest in marine science and maritime careers.

Explore aims to motivate students to develop technical skills and scientific literacy through active research interactions, thus moving them from being passive learners to active scientists. By engaging in independent research, students develop essential skills such as critical thinking, communication, problem solving, and collaboration. Early research experiences promote positive attitudes towards science, technology, engineering, and mathematics (STEM), whilst field-based research experiences nurture positive self-esteem, independence, and creative thinking in young learners.

Main findings

Six grant calls have been issued between 2016 and 2020. In total, 44 students have participated in the Explore programme. Research topics have spanned across a wide range of marine science topics, from exploratory studies on seagrass to natural product research and eco-engineering themes. Results from a number of research projects are currently being prepared as manuscripts for submission or have already been published in international journals. The first Young Marine Scientist Symposium was organised in June 2019, and the second was held in June 2021. The symposia brought together young marine scientists from Explore and other MSRDP projects to exchange research ideas and network with other young scientists.

Explore students hard at work

Mangroves at Pulau Semakau

Epilogue

THROUGH THE LOOKING GLASS

Contributed by Peter KL Ng[1], Staffan Kjelleberg[2], Serena LM Teo[3]

[1] Director, Marine Science Research and Development Programme, National Research Foundation
[2] Deputy Director, Marine Science and Development Programme, National Research Foundation; and Director, Singapore Centre for Environmental Life Sciences Engineering, Nanyang Technological University
[3] Facility Director, St. John's Island National Marine Laboratory, National Research Foundation; and Deputy Director, Tropical Marine Science Institute, National University of Singapore

Executive summary

Through the Marine Science Research and Development Programme, the National Research Foundation has created a multidisciplinary community of marine scientists engaged in national projects and civil society, anchored by St. John's Island National Marine Laboratory as a National Research Infrastructure, as well as several research-strong facilities in Singapore's institutes of higher learning. The Maritime and Port Authority (MPA) has synergised their data needs with the systems developed by the MSRDP and NRF's Marine Environment Sensing Network into a consolidated national database—the GeoSpace-Sea Initiative, which will harmonise the hydrospatial data needed to support maritime safety, coastal planning, marine science research and development, climate change research, and disaster response.

With this strong platform, it is now opportune to position Singapore as the regional nexus for marine science research in tropical Southeast Asia. To strengthen our knowledge and databases, it is necessary to extend research to a larger regional context that captures the diverse scenarios beyond our borders, enables sustainable use of surrounding transboundary sea space and effective conservation of ecosystem health, and improves our capacity for pre-emptive environmental management to sustain our global competitivity. Research initiated within the MSRDP on biogeochemical ecosystem processes, marine biodiversity inventories and invasive species, holobiont biology, biocorrosion, and marine plastics pollution are important areas wherein further translational research will need large-scale benchmarks. An integrated programme that supports scientific research collaborations with regional countries will result not only in high-impact science but the formation of beneficial networks among scientists from which we may leverage to improve the sustainability of the living environment around us.

Introduction

The marine environment plays an important role in enabling Singapore as a city state to deal with its multitude of national economic and security challenges (navigation, trade, water, food and energy security, safety, etc.). It is often seen as an additional space to cater for Singapore's expanding need for land, but current concepts for a sustainable liveable city to work, and an endearing home for residents, require a rethink as to how we better use the sea space. Dealing with national challenges beyond climate change as a coastal city in symbiosis with its marine environment is not a problem peculiar to Singapore. More than 60% of the world's population live in coastal areas and about two-thirds of cities with populations greater than 2.5 million are located along coastal areas. Many coastal cities are struggling to achieve continued viability in the face of over-exploitation or neglect of their marine environments. In our unique position, we have been able to achieve and maintain a good balance between economic development and a healthy ecosystem with rich marine biodiversity. As such, Singapore's relative success can be a reference model, enhancing the country's thought leadership in marine science and maritime affairs, and providing opportunities for the industry.

In 2015, the NRF established the Marine Science Research and Development Programme. In the six years of its tenure, the MSRDP has set a precedence for marine science research, and brought out the best in the island's resident scientists and their international collaborators. The programme enabled researchers from different disciplines and institutions to work together on a greater science mission for the country. The programme engaged 33 projects, eight institutions of higher learning, 88 research scientists, 119 other research staff, 51 higher degree students, and delivered more than 160 peer-refereed papers published—good results by any measure (for a summary of the research accomplishments, see page 12 in this volume).

Yet, such key performance indicators (KPIs) do not tell the whole story because many important attributes cannot be easily measured. As the architects and managers of the MSRDP, we have had a challenging but rewarding journey. The phrase 'through the looking glass' from Lewis Carroll's Alice in Wonderland books alludes to the unpredictability of the world we live in, reflecting what we do and why we do things the way we do. As the MSRDP now draws to a close, it is therefore useful for us to look at this programme 'through the looking glass'—and to suggest what the future will need.

The state of play

The MSRDP embarked on a proactive model for engaging, managing, and catalysing a complex multidisciplinary research domain such as that of marine science. The MSRDP went beyond straight-out competition to capture the best ideas for funding. It took a layered approach to develop novel ideas and engage the best people available locally, embedding them in a global network of top scientists. This helped create a new 'research culture' and laid the foundation for a multifaceted approach towards marine science in Singapore. It has led to excellent collaborative science that fosters understanding as well as protection of our marine ecosystems and enabling translational outcomes.

By working beyond institutional boundaries, traditional working spaces, silos, and bureaucracies, the MSRDP took an 'all of Singapore' approach to unite the best talents to build a marine research ecosystem that supports national needs. By 'interconnecting within', it also enabled the programme to connect beyond Singapore—it provided NRF with a focal point for all sciences, ideas, and proposals associated with the marine environment, a *de facto* 'clearing house' for these activities.

This approach has revitalised Singapore's marine science research culture. Beyond mere statistics, there is also a sociological outcome that is perhaps more important and durable than basic KPIs. The MSRDP created a community of marine scientists from different backgrounds, working together with agencies, NGOs, and civil society. This was a unified marine science community whose members freely exchange ideas and problems, and had a joint approach to dealing with national, regional, and international issues. It is these 'soft' deliverables that changed how we approach scientific challenges in a more cost-efficient and effective manner. It is a model for project management that we hope will continue for future science-based programmes.

Science in action

Local industry stands to benefit from more sustainable, science-based approaches to enhance productivity in the longer term. 'Green' practices, coupled with conservation consciousness, will be potent branding for our industries to excel in the new global economy. From a regulatory perspective, science helps inform and guide best practices to enable multi-agency activities to be more effective. The science involved also goes beyond what is needed for climate-related issues such as carbon credits and energy efficiency. It will enable marine spaces to be fully utilised as we attempt to integrate shipping, food security, recreation, and energy industries into an increasingly crowded sea space (Table 1). Our ability to solve these issues will have major ripple-on effects for the region and set the bar for what Singapore can achieve globally.

One lesson learnt from the MSRDP is that any future programme will also have to factor in commercial and stakeholder needs. In the MSRDP, research was linked to the needs of government agencies and statutory boards whenever possible. That being said, many aspects of the marine environment actually hold substantial commercial value. Indeed, private companies have shown much interest in marine science R&D even beyond climate and carbon needs, especially for aquaculture, antifouling, and anticorrosion technologies, managing marine pollution such as plastics, sensor technology, more robust environmental assessments, and modelling environmental impacts and mitigation science (Table 1). Moving forward, we need to fully integrate industry as part of the research whenever possible.

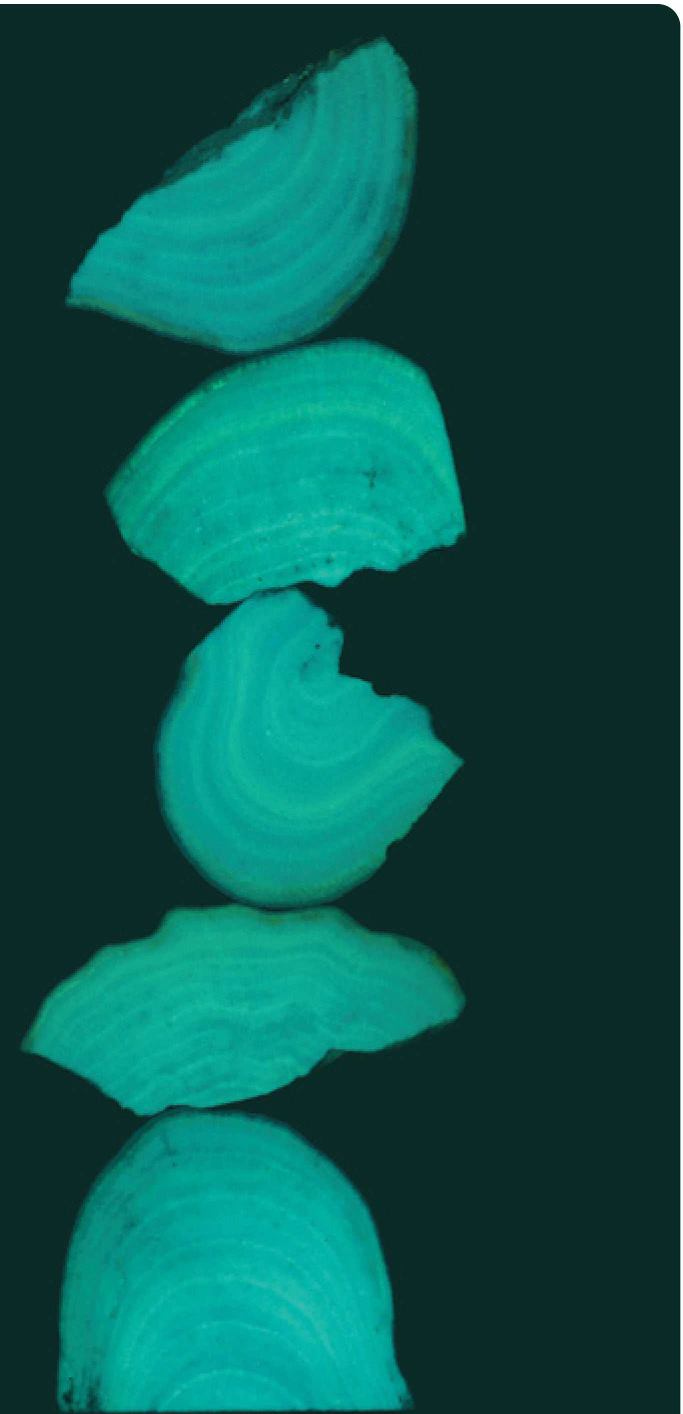
Beyond climate science

The success of the MSRDP has led directly to the establishment of a new programme centred on climate change—the Marine Climate Change Science (MCCS) programme. Conceptualised by NRF through the MSRDP, the MCCS has been operationalised by the National Parks Board (Ministry of National Development) as its implementing agency in 2021. The MCCS will focus on impending climate changes facing our seas and innovative research topics including 'blue carbon', long-term marine ecosystem resilience, and coastal eco-engineering. The knowledge generated will be important in positioning Singapore as a regional and international thought- and knowledge-leader in mitigative and applied nature-based climate change science for the tropical marine domain.

While MCCS is a major outcome of the MSRDP, it is not the successor. There is a tendency to believe that unless an environmental project is couched with the existential threat posed by climate change, it is deemed less worthy of support. Marine science, however, is not just about climate change challenges. Singapore also has a need to be a responsible steward to sustain a stable marine ecosystem, and this is best achieved through a comprehensive marine science programme. There are many domains that are important to study (Table 1), with regional and global impacts, and independent of the challenges climate change may impose.

The national prerogative: taking a regional perspective

As an island state, Singapore should not view its marine environment as a geographic boundary, but instead as an extension to a



Luminescent bands in *Porites* coral skeletons from around Southeast Asia

larger global economy. We already know this from programmes on climate modelling, weather prediction, hydrography, and maritime navigation as well as food supply chains and pandemic science. In this respect we need to embrace the DNA of our seafaring forefathers, to leverage on resources of the sea to a whole new level. To do so demands that marine science is woven back into the fabric of our economy at both regional and global levels, delivering solutions into the marketplace and for societal benefits. In short, the way ahead for marine science in Singapore is to go regional and international, while keeping Singapore as a knowledge node centred in the region. In the process, we can also internationalise our roles and capabilities. Research outcomes are by no means a zero-sum game!

Singapore is heavily dependent on global resources. In building our resource resilience (for food, water, energy, etc.) as a small island nation, we not only need strategies to boost self-reliance (local production) but also to diversify imports. A term currently used in the Singapore Food Agency's Singapore Food Story, 'growing overseas', is a strategy to be applied to other resources. For instance, if all goes well, by 2024, Singapore may be supplied by renewable energy from a floating solar farm located 50 kilometres away in Batam, Indonesia, through a subsea cable running across the Singapore Strait. Announced in July 2021, this $2.7 billion, 1,600-hectare world's largest floating solar farm is being built by Singapore's Sunseap Group.

The sea is a major connector in ASEAN. Just as fishes do not recognise geopolitical borders, trash, unwanted hitchhikers (marine invasive species), microbes, nutrients, and pollutants mix and flow across these interconnected marine realms. Marine issues cannot therefore be managed by one country;

Artificial embayments along East Coast Park

even if the problems are external to ASEAN, the issues are magnified within Southeast Asia. Problems of pollution, marine traffic (including port usage), invasive species, natural resources (from timber to fisheries), conservation, sustainable trade in bioresources, international treaties on ballast water, genetic resources of the high seas, etc., are essentially transboundary in nature and require close collaboration and sharing of data. This is only exacerbated in politically sensitive areas, such as the South China Sea.

As Singapore continues to increase engagement in shared regional resources, there is a need to accept shared responsibilities. Singapore is after all also heavily dependent on global data for it to strengthen its economy and capabilities. Singapore has an increasing role complementing our ASEAN partners in a multitude of ecological and sustainability issues, some aspects of which will overlap with our climate change challenges.

Singapore played a pivotal role in drafting the United Nations Convention on the Law of the Sea (UNCLOS) in 1982. Since then, it has held a prominent position in leading and formulating international agreements and activities for conservation and sustainable use of marine biological diversity, including its industrial and commercial development on an environmentally sustainable basis. Singapore currently chairs the intergovernmental UNCLOS conference aimed at establishing an international legally binding agreement for conservation and sustainable use of marine biological diversity of areas beyond national jurisdiction (BBNJ). This extends to the International Seabed Authority (ISA), which leased Singapore a plot in the central Pacific for future deep-sea mining. With technology comes an urgent demand for materials, and challenges for mineral prospecting in the high seas for the future.

International responsibilities beyond Singapore's waters are an important new stage in the country's plans to expand its geopolitical footprint. Many island states bordering BBNJ and ISA face biodiversity impacts as well as existential climate change challenges of sea-level rise. Singapore should also support these nations through the Alliance of Small Island States (AOSIS) (of which Singapore is a founder) through a broad-based marine science programme. Our marine science capacity needs to be in place when these activities ramp up. And more so considering that the country is intending to fulfil the 17 global Sustainable Development Goals (SDGs) set up by the United Nations in 2015.

Future proofing: unknown unknowns and unpredictability

As a US politician once quipped, 'There are also unknown unknowns—the ones we don't know we don't know.' This sentiment has proved to be applicable in many scenarios. There is an awful lot we do not know and even more we cannot imagine; we live in a very unpredictable world. This is particularly relevant for science and the scope of research needed to prepare for an uncertain future. In this challenging environment, what does the future hold for marine science in Singapore—as a country, and as a hub for science and knowledge generation?

A small island state like Singapore needs to be prepared and have the necessary capabilities to react when new challenges or opportunities suddenly arise. There is a strong case for IHLs to actively build a large and comprehensive body of knowledge that can be drawn upon when needed. Below are three cases where Singapore leveraged in-country, internationally recognised expertise when confronted with unexpected challenges.

Case 1. In 2003, Malaysia brought Singapore to the International Court of Justice for purported infringements of its waters. Singapore's response involved a science-based approach to resolve the challenge—what do the scientific facts and available data suggest? Scientific issues on the table ranged from physical oceanography to biodiversity science and fishery resilience. Expert scientists from both countries were called upon to examine scientific data to help lawyers argue the case. For example, the biodiversity present in the waters, past and present, and how it can be impacted and mitigated were addressed by Singapore biologists. One major outcome following the proceedings was that Singapore, through the National Parks Board and IHLs, embarked on a Comprehensive Marine Biodiversity Survey (2011–2016) to establish a biodiversity baseline for the country's marine fauna and flora.

Case 2. When Keppel Corporation decided to potentially invest in deep-sea mining in the central Pacific (the Clarion-Clipperton Fracture Zone), they needed the support of the Singapore government to apply to the International Seabed Authority. The ISA has strict protocols for environmental studies to be conducted and for the protection of the organisms present before mining can take place. In 2013, Keppel and the Ministry of Foreign Affairs sought advice from IHLs for deep-sea biology. Although this is not a science relevant to Singapore's economy (only shallow seas are in its exclusive economic zone), fortuitously, there were a few researchers who had been involved in deep-sea cruises organised with international colleagues in the Pacific and had published extensively on deep-sea animals. Exploratory 'blue-sky' science suddenly became useful for national needs. The ISA granted the contract to Keppel and Singapore in 2014.

Case 3. When UNCLOS in New York convened an intergovernmental conference on the conservation and sustainable use of marine biological diversity of areas beyond national jurisdiction in 2017, Singapore as the country chair sought biologists to advise the delegation. The topics that dominated the agenda were all over deep-water seas and on the nature of marine genetic resources, how surveys are conducted, how deep-sea organisms and habitats are studied, etc. Again, fortunately, expertise was available in the IHLs allowing the Singapore delegation to present strong and cogent arguments.

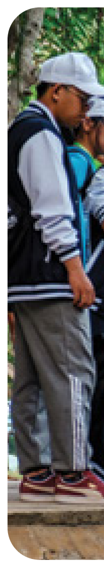
Setting the stage for marine science research in the future

The MSRDP has taken the unprecedented step to network the best marine scientists in Singapore, and while this may sound intuitive, it is not always the case in R&D environments. The programme has served to galvanise the country's marine science community to be a dynamic and well-respected group internationally. As a result, Singapore now enjoys global recognition for its collaborative marine science research and expertise. There have been bottom-up initiatives such as the Singapore Blue Plan that demonstrates the dynamism of the community, and many young marine scientists and professionals have been attracted to join. There is thus a need to support and grow a multidisciplinary and broad-based approach in marine science to strengthen and sustain this important national resource—maximising our most valuable asset: human resources.

As for facilities, NRF has made major investments to make St. John's Island National Marine Laboratory a National Research Infrastructure (NRI) to serve its national marine science needs. At the national level it is the focal point for marine science activities and is therefore propositioned as a regional nexus. As the MSRDP progressed and the knowledge accumulated, there arose an urgent need for a national integrated marine database; this triggered the establishment of the GeoSpace-Sea Initiative led by the Maritime and Port Authority of Singapore together with other government agencies and IHLs to consolidate, integrate, and harmonise existing and future marine data for better management of Singapore's sea space. The Lee Kong Chian Natural History Museum (LKCNHM) at the National University of Singapore has one of the largest collections of regional fauna. As a major biodiversity repository and node for Southeast Asian research in this field, the LKCNHM has extensive collaborations in the region, which have supported major bilateral marine surveys in the Philippines, Indonesia, Thailand, Malaysia, Brunei, Vietnam, Christmas Island, and Cocos (Keeling) Islands over the last 20 years, the most recent being the deep-sea cruise to southern Java. Of the several NRF-funded Research Centres for Excellence (RCE), the Singapore Centre for Environmental Life Sciences Engineering (SCELSE) in particular, has a large number of programmes closely connected with microbes, fouling, genomics, holobionts, and biomimetics in the marine realm.

On the networking and education front, there are active collaborative programmes between IHLs and private companies that should be leveraged as well. Currently, IHL scientists participate actively in working groups of the ASEAN Sub-Committee on Marine Science and Technology (SCMSAT) and the UN Intergovernmental Oceanographic Commission's Sub-Commission for the Western Pacific (WESTPAC). In the private sector, Temasek Foundation partners with SJINML and IHLs to engage with ASEAN students and scientists for research and education (e.g., STEP Environment Camp for ASEAN youth, and STEM for University Educators Programme in ASEAN), while many companies support marine science–related projects at IHLs.

The concept of networking across countries to study the marine environment is not new but is poorly developed in Asia. Marine laboratories across the United States, including Hawaii, are networked to collect marine data across the Eastern Pacific and Western Atlantic. There are various programmes within the European Union that not only link marine infrastructure but also involve projects across laboratories to collect environmental data. These initiatives reflect the importance of large-scale geographic data in environmental science. For the region, the 2010 ASEAN-India programme 'Extent of Transfer of Alien Invasive Organisms in South/Southeast Asia Region by Shipping' serves as a good example of how academic networks collaborate to further our knowledge of marine biology in tropical Southeast Asia. Led by Singapore and India, the programme attracted participation from all ASEAN partners for sampling and data collection and provided new information on



pest organisms in tropical seas. Indonesia and the Philippines have since adopted roles as the Lead Partnering Countries representing Southeast Asia in the International Maritime Organization's GloFouling Partnerships Project to manage marine invasive species.

A regional nexus centred in Singapore will draw on existing MOUs and research ties, particularly with the adjacent countries Indonesia and Malaysia. Singapore is seen as a knowledge node, that is technologically and scientifically strong. As such, Singapore can connect expertise from other nodes in the US, Europe, China, India, Japan, and Australia, as well as Southeast Asia; especially given our central geographic position. Regional countries have expressed a desire to learn from Singapore, providing opportunities for strong bilateral partnerships.

In summary, Singapore's place in marine sciences has been strengthened substantially by the MSRDP. To take this success to new levels requires us to think beyond the island. For true relevance in marine science, its coverage needs to broaden. We also need a new paradigm for driving marine science research in Singapore beyond climate change. Our posit therefore is that Singapore must leverage on our strengths and advantages to establish a new regional marine science research programme. It will use the MSRDP model of integrating resources to maximise outcomes and take marine research and deliverables for Singapore to a higher level.

A nexus for regional marine science research?

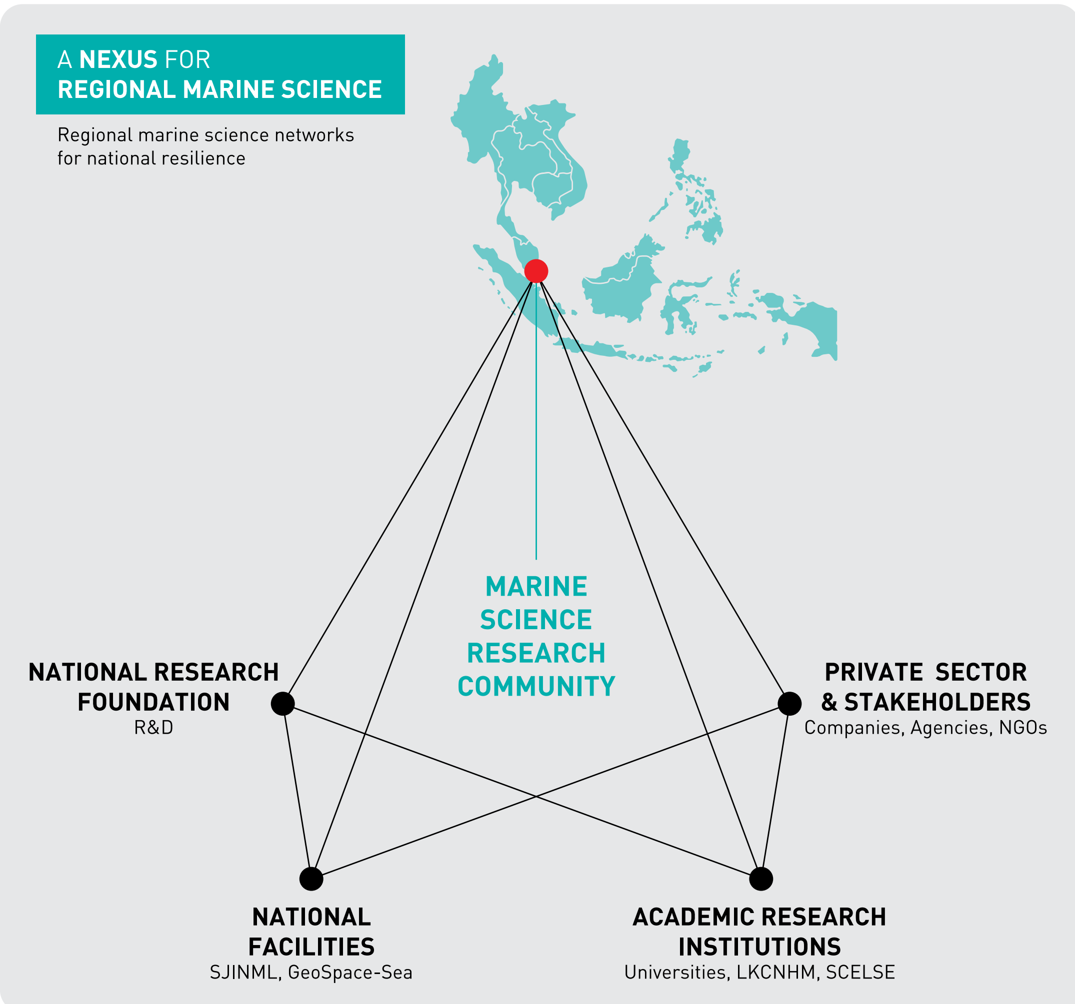
The argument that marine science cannot be limited to national boundaries is a critical one. Around 70% of the earth is sea, and the use of the sea to connect societies and to support human existence requires a sound understanding of global and regional marine environments. A strong and dynamic marine science community is important in safeguarding Singapore's interests (in both existing and emerging challenges) and to play a leading role in international affairs. The sea is also a treasure trove for scientific discovery to deal with new and emerging problems. That Singapore should seek to play a leading role in marine science in the region is critical because its host marine environment extends beyond our limited sea space. The health and vitality of the regional seas around Singapore are vital to our survival and success.


STEP Environment Camp for ASEAN youth

Southeast Asia has 2.5% of the world's ocean surface, but about 16% of its coastline. The area also hosts 30% of coral reef ecosystems, one-third of mangrove ecosystems, 17% of seagrass ecosystems, and a large variety of coastal and marine ecosystems with high species richness.

The knowledge obtained through the MSRDP led the team to realise that to fully understand our marine environment and use the data more effectively, we must extend our research and knowledge gathering far beyond our shores. As an analogy, to understand rainfall patterns in Singapore so we can better manage our water needs and mitigate flooding with accurate predictive models, we have to look at regional weather phenomena and factor in this data.

There is consilience—the necessary pillars in establishing a regional marine research nexus are already in Singapore (Figure 1). This marine nexus will amalgamate existing facilities and institutes with the manpower cum capabilities established under the MSRDP, with the strong existing regional networks (which



↑ Figure 1

should still be expanded) and synergised with Singapore's global science connectivity. This nexus will then design and implement regional research projects that will generate new ideas, deeper knowledge, and big data to help Singapore strengthen its overall global competitiveness across various fronts, including in food security, diplomacy, and international responsibilities. In addition, the marine nexus will help train a new generation of marine scientists, not just in Singapore but regionally. Overall, the nexus will foster sustainable use of our sea space, enable effective conservation of the ecosystem health, improve our capacity for pre-emptive environmental management, and enable Singapore to sustain its global competitiveness across many fronts, from education to industry.

Leadership in marine science and maritime affairs offers an important platform for Singapore as a small maritime state to remain relevant and to punch above its weight in global affairs. An effort to establish a regional nexus centred in Singapore will offer a strong platform for Singapore to play a leadership role in the region and among the community of small island states.

A healthy planet is inextricably linked to a healthy ocean; however, only 10% of the oceans have been studied by scientists. In the next decade, we must make important decisions about their management. That is why in 2017, UNESCO declared a United Nations Decade of Ocean Science for Sustainable Development (2021–2030), which mobilised the scientific community, policymakers, businesses, and civil society to strengthen innovation in marine research and technology, and to engage in international cooperation in this field. This strengthens the coordination of research programmes, observation systems, capacity building, marine space planning, and the reduction of maritime risks, as well as improving the management and utilisation of marine and coastal resources. With the experience of the MSRDP as a project to promote success in Singapore, it is hoped that the government of Singapore will continue to support the programme and continue to contribute to humanity in conjunction with this five-year marine scientific research programme.

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Table 1. Some key challenges for Singapore marine R&D

Environmental impact assessment (EIA) frameworks	• Develop capacity and technologies to manage marine ecosystem-specific threats for tropical and equatorial regions • Measure environmental parameters at relevant resolution and scales to obtain appropriate baselines for EIA in various parts of Southeast Asia • Establish appropriate practical criteria for conducting EIA, monitoring impacts, and post-developments • Develop stronger EIA frameworks with better regional data that capture connectivity, impacts, and regional issues more accurately
Shipping industry	• Better understand shipping effects on tropical marine and coastal ecosystems • Develop sustainable practices for port development, ship design, and construction • Enhance management of marine biosecurity in shipping industry (invasive species in ballast water, biofouling management) • Develop and manage green port to enhance sustainability of the tropical marine environment, beyond fuel efficiency and carbon reduction • Initiate active dialogue and knowledge-sharing between academia and industry in local and regional shipping hubs for proactive management of coastal shipping
Coastal infrastructure and its protection	• Develop coastal infrastructure that conserves critical ecosystem functions • Better manage natural and engineered habitats such as mangroves, seawalls, reclaimed land, and floating infrastructure • Better understand how the marine environment impacts erosion and corrosion, for developing improved materials for coastal infrastructure

Marine invasive species	• Integrate assessments of marine invasive pests in Singapore's waters and associated risks • Develop national invasive pest management strategy that addresses incursions from different marine industries (shipping, aquaculture, etc.) • Understand chemistry (larval settlement), physical oceanography (spread), and biology (life history and ecology) on a regional scale to mitigate spread of invasive species
Marine pollution	• Improve understanding of ecosystem impacts from emerging anthropogenic pollutants (e.g., plastics, heavy metals, pesticides, drugs etc.) • Develop risk assessment framework and environmental safety standards to evaluate valorised new materials to be used in marine environment applications
Food security	• Improve aquaculture practices to minimise impact to the environment and integrate food safety with environment quality goals • Apply science-based approaches to management and regulation of fishery practices to promote sustainability of marine fisheries and prevent overfishing • Apply science-driven risk mapping to manage seafood diversification
Human health and the ecosystem	• Apply emerging understanding of holobiont biology (host organism living in association with microbial communities) to promote ecosystem resilience and disease resistance • Improve understanding of relationships between marine ecosystems and human health
Advanced materials	• Improve documentation of marine diversity to support targeted bioprospecting • Support programmes that enable novel pharmaceuticals and materials derived from marine products, from discovery to translation and commercialisation
Marine technology	• Advance marine engineering that is resistant to biofouling and biocorrosion • Advance technologies for noisy and turbid coastal environments
Environment policy	• Improve integration of legal and social policy development into marine science and environment research
Blue economy	• Establish frameworks for expanded use of sea space • Develop concepts for integrated floating cities as well as assessing and managing associated environmental impacts • Enable integration of maritime economy for energy (floating solar panels, windfarms, tidal energy stations), food, and/or floating data centres (with emphasis on studying, managing, and mitigating environmental impacts)

Copperbanded butterflyfish, *Chelmon rostratus*

APPENDIX

MSRDP outputs up to the end of Financial Year 2020

Journal publications arising from the MSRDP

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Technology disclosures arising from the MSRDP

S/N	Inventors	Title of disclosure	Covering countries	Filing office	Date of filing	MSRDP projects
1	Tan BT, Wu P	Biomimetic design of Nearly-Zero-Energy water harvesters by patterned strain-engineered surfaces	Worldwide	SUTD	10-Apr-19	P-28
2	Lauro F	Modelling genetic data from a time series of Singapore's coastal waters	Singapore	NTUitive Pte Ltd	5-Mar-19	P-13
3	Chai CLL, Tong YW, Cao X, Choo MZY	Complementary template-imprinted mix-and-match molecular imprinted quantum dots (QD@MIP) composite library for algal toxin detection		Submitted		P-21
4	Pek YS, Birch WR, Tan WS, Rice SA, McDougald D	Coatings that enhance the settlement and growth of marine organisms	Singapore		29-Sep-20	P-05

Patents arising from the MSRDP

S/N	Inventors	Title of patent	Covering countries	Filing office	Date of filing	Filing reference
1	Lee S, Bae S	Non-provisional patent: DyeTox13 Green C-2 Azide For Differentiation of Viable and Nonviable Bacteria Using PCR	Singapore	Singapore	15-Mar-18	10201802132Q
2	Lee S, Bae S	DyeTox13 Green C-2 Azide For Differentiation of Viable and Nonviable Bacteria Using PCR	International	Singapore	15-Mar-19	PCT/ SG2019/050143.
3	Tan BT, Wu P	Biomimetic design of Nearly-Zero-Energy water harvesters by patterned strain-engineered surfaces	Worldwide	SUTD	10-Apr-19	

MSRDP research staff

S/N	Project	Name	Manpower category
1	P01	Cheah Hee	Research Assistant
2	P01	Chiang Li Ching Elaine	Research Assistant
3	P01	Fu Jing	Research Engineer
4	P01	Jiang Dongyue	Research Fellow
5	P01	Lee Seunguk	Research Fellow
6	P01	Park Jongsung	Research Fellow
7	P03	Aaron Loh An Rong	Research Assistant
8	P03	Andrew Geoffrey Bauman	Senior Research Fellow
9	P03	Benjamin John Wainwright	Research Fellow
10	P03	Chen Mengli	Research Fellow
11	P03	Chen Zhiyuan	Research Assistant
12	P03	Ho Xin Yi	Research Assistant
13	P03	Jain Sudhanshi Sangeev	Research Assistant
14	P03	Jani Thuaibah Isa Tanzil	Senior Research Fellow
15	P03	Jovena Seah	Research Assistant
16	P03	Lindsey Kane Deignan	Research Fellow
17	P03	Neo Mei Lin	Research Fellow
18	P03	Oh Ren Min	Research Assistant
19	P03	Ong Maria Rosabelle Kwan	Research Assistant
20	P03	Phyllis Kho Yu Yi	Research Assistant
21	P03	Pwa Keay Hoon Veron	Research Assistant
22	P03	Sam Shu Qin	Research Assistant
23	P03	Teh Jing Jie	Research Assistant
24	P03	Tiffany Goh Zhenyan	Research Assistant
25	P03, P05	Ang Chiam Foong Ambert	Research Assistant
26	P04	Erwan Bertevas	Research Fellow
27	P04	Le Cao Khoa	Research Fellow
28	P04	Lee Ai Chin	Research Associate
29	P04	Ow Yan Xiang	Research Fellow
30	P04	Suryati Ali	Research Associate
31	P04	Wang Di	Research Fellow

S/N	Project	Name	Manpower category
32	P04	Wong Lan Li	Research Assistant
33	P04	Wong Pui Yee	Research Assistant
34	P04, P03	Tan Yee Keat	Research Assistant
35	P05	Amanda Hsiung Rouwen	Research Assistant
36	P05	Chang Chia-Chen	Research Fellow
37	P05	Du Rosa Celia Poquita	Research Fellow
38	P05	Elizabeth Crenshaw Heery	Research Fellow
39	P05	Hana Binte Abdul Wahab Marican	Research Assistant
40	P05	Hu Jie	Research Engineer
41	P05	Ignacio Barranco Granged	Research Engineer
42	P05	Janine Ledet	Research Fellow
43	P05	Kikuzawa Yuichi Preslie	Research Assistant
44	P05	Kingsley Griffin	Research Fellow
45	P05	Lee Yen-Ling	Research Assistant
46	P05	Loke Hui Ling Lynette	Research Fellow
47	P05	Loo Poh Leong	Research Fellow
48	P05	Rania Selo Hartanto	Research Assistant
49	P05	Tan Wen Ting	Research Assistant
50	P05	Wu Yun-Ta	Research Fellow
51	P05	Yuri Shona Pek	Senior Specialist II
52	P05	Zhao Kuifeng	Research Fellow
53	P05, P03	Stephen Summers	Senior Research Fellow
54	P05, P07	Ying Shu Min Lynette	Research Assistant
55	P07	Gomathi Mahadevan	Research Assistant
56	P07	Miss Siti Kamariah Binte Ahmad	Research Assistant
57	P07	Tay Teresa Stephanie	Research Assistant
58	P08	Muthupillai Jayaraj Muthukumar	System Analyst
59	P11	Kristy Chang	Research Assistant
60	P11	Kyle Morgan	Research Fellow
61	P11	Tan Su Ying	Research Assistant
62	P12	Chong Yik Yan	Research Assistant

S/N	Project	Name	Manpower category
63	P12	Gao Ya	Research Assistant
64	P12	Lee Kai Peng	Research Engineer
65	P12	Lucinda Elizabeth Doyle	Research Fellow
66	P12	Nicholas John Tan Jie Hao	Research Assistant
67	P12	Viduthalai Rasheedkhan Regina	Research Fellow
68	P12, P13	Caroline Chenard	Research Fellow
69	P13	Avneet Kaur	Research Assistant
70	P13	Christaline George	Research Assistant
71	P15, P34	Marshall Ong Ji Fa	Research Associate
72	P15, P34	Tong Jie Lin Jasmine	Research Associate
73	P15, P34	Chin Seow Fong, Joyce	Research Assistant
74	P18	Lee Co Sin	Research Assistant
75	P18	Shubha Vij	Research Fellow
76	P18	Tay Ywee Chieh	Research Fellow
77	P19	Shingate Prashant Narendra	Research Fellow
78	P19	Tang Qian	Research Fellow
79	P19	Tay Boon Hui	Research Officer
80	P20	Chua Yu Han Gabriel	Research Engineer
81	P20	Kee Boon Leng	Engineer
82	P20	Koay Teong Beng	Senior Engineer
83	P20	Low Teck Khoon	Senior Engineer
84	P20	Too Yuen Min	Research Fellow
85	P20	Win Le Yi Thant Annie	Laboratory Executive
86	P21	Ang Wei Jun	Research Assistant
87	P21	Cao Xujun	Research Assistant
88	P21	Choo Zheng Yuan Malcolm	Research Assistant
89	P21	Johannes Nathaniel Liew Min Hui	Research Assistant
90	P22	Caryn Pang Zhiqin	Research Assistant
91	P22	Choo Yen Ling	Research Assistant

S/N	Project	Name	Manpower category
92	P22	Hiong Kum Chew	Research Fellow
93	P22	Pavarne Shantti Sivalingam V M	Research Assistant
94	P29	Bui My Hanh	Research Assistant
95	P29	Cai Hao Ali	Research Assistant
96	P29	Joao Diogo Guimaraes Gouveia	Research Fellow
97	P29	Muhammad Hafiz Bin Ismail	Research Fellow
98	P29	Snehasish Basu	Research Fellow
99	P30	Tan Shi Ming	Research Fellow
100	P32	Chen Shuang	Research Associate
101	P32	Nivedita Sanwlani	Research Fellow
102	P32	Woo Oon Yee	Research Associate
103	P33	Lim Wenxiong Elton	Research Associate
104	P33	Nandini Shome	Research Fellow
105	P33, P45	Chan Siew Herng Stan	Research Fellow
106	P38	Yip Zhi Ting	Research Assistant
107	P39	Lim Chin Sing	Research Associate
108	P40, P08	Ginju Soumya Karisseril Soman	Assistant Manager
109	P40, P08	Maria Su Qiyan	Manager
110	P40, P46, P08	Wang Jiqin	Lead Systems Engineer
111	P42	Hari Vishnu	Research Fellow
112	P43	Oh Kai En Rachel	Research Associate
113	P44	Lim Cheng Ling	Research Associate
114	P46	Kim Dong Eon	Research Fellow
115	P46	Liu Jiandong	Research Fellow
116	P46	Soh Chong Wee Evan	Senior Software Engineer
117	P46	Wang Mengyu	Research Associate
118	P46, P08	Balamurali Cattavarayane	Lead Systems Analyst
119	P46, P08, P44	Choo Heng Kek	Project Manager

Polytechnic students trained

S/N	Name	Project	PI	Institution	Internship start date	Internship end date	Diploma
1	Jonathan Lam	P15	Tan Lik Tong	NTU-NIE	20-Mar-17	6-Aug-17	Diploma in Marine Science and Aquaculture (DMAC), RP
2	Nabilah Sajerin	P15	Tan Lik Tong	NUS-TMSI	20-Mar-17	6-Aug-17	Diploma in Marine Science and Aquaculture (DMAC), RP
3	Teiw Kai Jie	P15	Tan Lik Tong	NTU-NIE	18-Sep-17	4-Feb-18	Diploma in Marine Science and Aquaculture (DMAC), RP
4	Shawn Pang Chong Hor	P15	Tan Lik Tong	NTU-NIE	12-Mar-18	29-Jul-18	Diploma in Marine Science and Aquaculture (DMAC), RP
5	Chua Zhisheng	P12	Scott Rice/ Enrico Marsili	NTU-SCELSE	16-Apr-18	7-Dec-18	Diploma in Biomedical Sciences, SP
6	Patrick Lin Hanrong	P12	Scott Rice/ Enrico Marsili	NTU-SCELSE	12-Mar-18	29-Jul-18	Diploma in Biotechnology (DBIO), RP
7	Ang Cheah Whee	P12	Scott Rice/ Lucinda Doyle	NTU-SCELSE	12-Mar-18	29-Jul-18	Diploma in Biotechnology (DBIO), RP
8	Sureshkumar Mithusha	P12	Scott Rice/ Lucinda Doyle	NTU-SCELSE	12-Mar-18	29-Jul-18	Diploma in Biotechnology (DBIO), RP
9	Halimah Bte Razali	P13	Federico Lauro	NTU	12-Mar-18	29-Jul-18	Diploma in Marine Science and Aquaculture (DMAC), RP
10	K Karthik S/O Kalidoss	P22	Neo Mei Lin	NUS-TMSI	12-Mar-18	29-Jul-18	Diploma in Marine Science and Aquaculture (DMAC), RP
11	Nurul Atiqah Binte Mohd Iwan	P22	Neo Mei Lin	NUS-TMSI	17-Sep-18	3-Feb-19	Diploma in Marine Science and Aquaculture (DMAC), RP
12	Wang Jun Yuan	P19	Oliver Chang	RP	12-Mar-18	29-Jul-18	Diploma in Environmental Science (DENV), RP
13	Colin Lee Zheng Dao	P19	Oliver Chang	RP	12-Mar-18	29-Jul-18	Diploma in Marine Science and Aquaculture (DMAC), RP
14	Elisha Tay Kai Lin	P19	Oliver Chang	RP	18-Sep-17	4-Feb-18	Diploma in Marine Science and Aquaculture (DMAC), RP

S/N	Name	Project	PI	Institution	Internship start date	Internship end date	Diploma
15	Clarice Tng Jia Wee	P19	Oliver Chang	RP	18-Sep-17	25-Feb-18	Diploma in Environmental Science (DENV), RP
16	Shirley Loe Xuan Lin	P19	Frank Rheindt	NUS-DBS	17-Sep-18	3-Feb-19	Diploma in Marine Science and Aquaculture (DMAC), RP
17	Vanisreesellam D/O Selvandran	P19	Frank Rheindt	NUS-DBS	17-Sep-18	3-Feb-19	Diploma in Environmental Science (DENV), RP
18	Amryn Dahnia bte Mohamed Zaili	P19	Jasmin Lim	RP	9-Sep-19	24-Jan-20	Diploma in Marine Science and Aquaculture (DMAC), RP
19	Bentley Boo Cheng Kang	P19	Jasmin Lim	RP	9-Sep-19	24-Jan-20	Diploma in Marine Science and Aquaculture (DMAC), RP
20	Lucas Chew Ming En	P35	Neo Mei Lin	TP	27-Jul-20	24-Jan-21	Diploma in Veterinary Technology
21	Aloysius Tan Kai Jun	P18	Henning Seedorf	TLL	17-Sep-18	3-Feb-19	Diploma in Marine Science and Aquaculture (DMAC), RP
22	Natalie On Kei-Yan	P18	Henning Seedorf	TLL	22-Oct-18	3-Feb-19	Diploma in Marine Science and Aquaculture (DMAC), RP
23	Jonathan Yeo Thian Ann	P05	Tan Koh Siang	NUS-TMSI	12-Mar-18	29-Jul-18	Diploma in Marine Science and Aquaculture (DMAC), RP
24	Lim Ying Xian	P05	Tan Koh Siang	NUS-TMSI	17-Sep-18	3-Feb-19	Diploma in Marine Science and Aquaculture (DMAC), RP
25	Regan Chong	P05	Tan Koh Siang	NUS-TMSI	17-Sep-18	3-Feb-19	Diploma in Environmental Science (DENV), RP
26	Chan Jia Qi Jaclyn	P05	Tan Koh Siang	NUS-TMSI	11-Mar-19	28-Jul-19	Diploma in Marine Science and Aquaculture (DMAC), RP
27	Goh Qiu Ting	P05	Tan Koh Siang	NUS-TMSI	9-Sep-19	26-Jan-20	Diploma in Marine Science and Aquaculture (DMAC), RP
28	Germaine Lee Kai Lin	P05	Tan Koh Siang	NUS-TMSI	9-Mar-20	26-Jul-20	Diploma in Marine Science and Aquaculture (DMAC), RP

S/N	Name	Project	PI	Institution	Internship start date	Internship end date	Diploma
29	Monteiro Isabel Joy	P05	Tan Koh Siang	NUS-TMSI	15-Jul-21	30-Jul-21	Diploma in Marine Science and Aquaculture (DMAC), RP
30	Oh Jing Wen, Joseph	P18	Henning Seedorf	TLL	1-Apr-19	16-Aug-19	Diploma in Marine Science and Aquaculture (DMAC), RP
31	Yoon Tae Won Dedrick	P18	Henning Seedorf	TLL	1-Apr-19	16-Aug-19	Diploma in Marine Science and Aquaculture (DMAC), RP
32	Soh Jia Pin	P18	Henning Seedorf	TLL	9-Sep-19	26-Jan-20	Diploma in Marine Science and Aquaculture (DMAC), RP
33	Anneliese Chua Pei Shing	P18	Zeehan Jaafar	NUS-DBS	9-Mar-20	26-Aug-20	Diploma in Marine Science and Aquaculture (DMAC), RP
34	Janice Siau Yu Xin	P18	Zeehan Jaafar	NUS-DBS	9-Mar-20	26-Aug-20	Diploma in Marine Science and Aquaculture (DMAC), RP
35	Gaynah Javier Dablo	P33	Stefan Wuertz	NTU-SCELSE	9-Mar-20	26-Jul-20	Diploma in Marine Science and Aquaculture (DMAC), RP
36	Hannah Yeo Xiu Hui	P18	Henning Seedorf	TLL	9-Mar-20	26-Jul-20	Diploma in Marine Science and Aquaculture (DMAC), RP
37	Phang Kai Qian	P05	Peter A Todd	NUS-DBS	14-Sep-20	31-Jan-21	Diploma in Marine Science and Aquaculture (DMAC), RP
38	Eric Wee Sin Kiat	P07	Serena Teo	NUS-TMSI	20-Mar-17	6-Aug-17	Diploma in Marine Science and Aquaculture (DMAC), RP
39	Theophilus Seah	P07	Serena Teo	NUS-TMSI	18-Sep-17	4-Feb-18	Diploma in Marine Science and Aquaculture (DMAC), RP
40	Farzana Binte Suhaimi	P07	Serena Teo	NUS-TMSI	12-Mar-18	24-Aug-18	Diploma in Molecular Biotechnology, NYP
41	Axel Yeo Wee Ann	P07	Serena Teo	NUS-TMSI	30-Jul-18	25-Jan-19	Diploma in Biotechnology, TP
42	Joel Ng Hong Swee	P07	Serena Teo	NUS-TMSI	9-Sep-19	26-Jan-20	Diploma in Marine Science and Aquaculture (DMAC), RP

S/N	Name	Project	PI	Institution	Internship start date	Internship end date	Diploma
43	Muhammad Luthfi Hadi Bin Mohamed Khalid	P07	Serena Teo	NUS-TMSI	9-Mar-20	26-Jul-20	Diploma in Marine Science and Aquaculture (DMAC), RP
44	Chen Shi Ting	P34	Yang Liang	NTU-SCELSE	1-Mar-18	30-Apr-18	Diploma in Biomedical Sciences, TP
45	Nur 'Afifah Binte Mohd Sean	P28	Serena Teo	SUTD	17-Sep-18	3-Feb-19	Diploma in Marine Science and Aquaculture (DMAC), RP
46	Jovin Leong Wai Feng	P28	Serena Teo	SUTD	18-Mar-19	13-Sep-19	Diploma in Chemical Engineering, TP
47	Marcus Renjie Lee	P03	Jani TI Tanzil	NUS-TMSI	22-Jun-20	12-Feb-21	SP
48	Sheena Heng	P03	Jani TI Tanzil	NUS-TMSI	27-Jul-20	22-Jan-21	Diploma in Veterinary Technology, SP
49	Calvin Leow Jiah Jay	P04	Ooi Seng Keat	NUS-TMSI	9-Mar-20	26-Jul-20	RP
50	Than Shermaine	P25	Tan Koh Siang	NUS-TMSI	11-Mar-19	28-Jul-19	Diploma in Marine Science and Aquaculture (DMAC), RP
51	Hana Soh	P25	Tan Koh Siang	NUS-TMSI	9-Mar-20	26-Jul-20	Diploma in Marine Science and Aquaculture (DMAC), RP

Undergraduates who went on overseas placements

S/N	Student name	Attachment period	Institution of attachment	Country of attachment	Project title	University
1	Inez Yi-Ling Alsagoff	21-May-18 to 6-Jul-18	Askö Laboratory, Stockholm University	Sweden	The effect of warming on predation intensity of the three-spine stickleback *Gasterosteus aculeatus* in the Baltic Sea	NUS
2	Jananee D/O Prakash Krishnan	8-May-18 to 19-Jun-18	University of Plymouth	UK	Does plankton abundance differ at different tidal states and depths?	NUS
3	Muhammad Syafiq B Mohd Noor	18-Jun-18 to 8-Aug-18	Royal Netherlands Institute of Sea Research	Sweden	A study on cliff formation in seagrass meadows using field flumes	NUS

S/N	Student name	Attachment period	Institution of attachment	Country of attachment	Project title	University
4	Clarence Sim Wei Hung	28-May-18 to 13-Jul-18	Marine Spatial Ecology Lab, University of Queensland	Australia	Survivorship of coral recruits in post-disturbance rubble beds in Vabbinfaru Island, Maldives	NUS
5	Jens Wira	22-Jun-18 to 8-Aug-18	Institute of Marine and Environmental Technology, University of Maryland	USA	Polyketide synthesis in *Amphidinium carterae* under varying growth conditions	NUS
6	Esther Koh Ai Ning	22-Jun-18 to 8-Aug-18	Institute of Marine and Environmental Technology, University of Maryland	USA	Polyketide synthases in toxin production for different strains of *Amphidinium carterae*	NUS
7	Yong Lei Xin (Clara)	21-Jun-18 to 10-Aug-18	University of Plymouth	UK	Effects of artificial substrate complexity and engineer species on subtidal ascidian diversity	NUS
8	Denise Ong Rui Ying	13-Jun-18 to 9-Aug-18	Tvärminne Zoological Station, University of Helsinki	Finland	Is *zostera marina* growth boosted in communities where plant species have different trait values?	NUS
9	Lee Hui Yian Theodora	11-Jun-18 to 10-Aug-18	Molecular Invertebrate Systematics and Ecology Lab, University of the Ryukyus	Japan	Changes in coral diversity in Nakagusuku Bay, Okinawa, Japan since 1975–76	NUS
10	Edwin Tan Yi Wei	11-Jun-18 to 10-Aug-18	Molecular Invertebrate Systematics and Ecology Lab, University of the Ryukyus	Japan	Genetic variation of symbiodiniaceae in *Palythoa tuberculosa* on Palau using the hypervariable PSBA non-coding region	NUS
11	Lewis Low Jie Qi	26-Jun-18 to 9-Aug-18	Prince of Songkla University Hat Yai	Thailand	Characterising chloroplast avoidance movement in an intertidal seagrass, *Halophila ovalis*, under irradiance stress	NUS
12	Choo Min Yi	26-Jun-18 to 11-Aug-18	Royal Netherlands Institute for Sea Research (Texel)	Netherlands	Interactions between sand wave sediment composition and their benthic community	NUS
13	Loh Ling Sheng	26-Jun-18 to 11-Aug-18	Royal Netherlands Institute for Sea Research (Texel)	Netherlands	An interplay of biotic and abiotic factors in shaping North Sea macrobenthic communities	NUS

S/N	Student name	Attachment period	Institution of attachment	Country of attachment	Project title	University
14	Quek Zhiqin, Vanessa	12-Jun-18 to 3-Aug-18	University of Hiroshima	Japan	Giant clam faecal pellets as possible zooxanthellae vectors	NUS
15	Lim Wei Zhi	2-Jun-18 to 23-Nov-18	National Museum of Marine Biology and Aquarium	Taiwan	Husbandry of sea turtles and the detection of *Chelonid herpesvirus* 5 (ChHV5) in the fibropapillomas (FP) of Fpridden	NUS
16	Ong Hwee Peng	11-Dec-17 to 20-Apr-18	National Museum of Marine Biology and Aquarium	Taiwan	Development and application of physiological characteristics, haematological and plasma biochemistry profiles to monitor health statuses of unhealthy sea turtles in rehabilitation	NUS
17	Claudia Kiang Jin Hong	11-Dec-17 to 20-Apr-18	National Museum of Marine Biology and Aquarium	Taiwan	Monitoring the well-being and health status of reared beluga whales (*Delphinapterus leucas*) in NMMBA through microbiological, molecular biological, physiological, behavioral and acoustic parameters	NUS
18	Wong Huai Hui	11-Dec-17 to 20-Apr-18	National Museum of Marine Biology and Aquarium	Taiwan	Investigate the cytotoxic activity of marine natural products	NUS
19	Tay Yuke Ling	11-Dec-17 to 20-Apr-18	National Museum of Marine Biology and Aquarium	Taiwan	Monitoring the well-being and health status of reared beluga whales (*Delphinapterus leucas*) in NMMBA through microbiological, molecular biological, physiological, behavioural and acoustic parameters	NUS
20	Lee Ling Shin	11-Dec-17 to 20-Apr-18	National Museum of Marine Biology and Aquarium	Taiwan	Mesocosm experiment to investigate possible factors leading to sudden mass morality of tropical seagrasses	NUS
21	Cham Soon Kiat Joseph	4-Apr-19 to 1-Jul-19	University of Auckland	New Zealand	Student Exchange Programme	NUS
22	Sirius Ng Zheng Hui	4-Apr-19 to 1-Jul-19	University of Auckland	New Zealand	Student Exchange Programme	NUS
23	Lim Jun An	19-May-19 to 28-Jul-19	Marine Conservation Cambodia	Cambodia	Undergraduate Professional Internship Programme	NUS
24	Pauline Wan	19-May-19 to 12-Jun-19	Marine Conservation Cambodia	Cambodia	Non-credit bearing programme	NUS

S/N	Student name	Attachment period	Institution of attachment	Country of attachment	Project title	University
25	Prasha Maithani	7-Jun-19 to 5-Aug-19	Royal Netherlands Institute of Sea Research	Netherlands	Resilience of tidal flats to rising sea levels: sediment dynamics	NUS
26	Chua Chun Yin Celine	1-May-19 to 31-Aug-19	Curtin University	Australia	Sedimentological signatures of coral reef islands along the coast of Western Australia	NUS
27	Clarence Sim Wei Hung	6-Jun-19 to 4-Aug-19	University of the Ryukyus	Japan	Effects of coastal development on the prevalence of coral diseases in Okinawa, Japan	NUS
28	Nikita Choudhary	6-Jun-19 to 4-Aug-19	University of the Ryukyus	Japan	Phylogenetic study on Smithsonian Museum specimen soft coral *Clavularia* (Cnidaria: Octocorallia)	NUS
29	Chew Chin Wei	31-May-19 to 27-Jul-19	University College Cork	Ireland	A preliminary study on the health status of *A. modestus* on the southern Irish coast	NUS
30	Justin Chia Yi Pin	31-May-19 to 27-Jul-19	University College Cork	Ireland	Effect of shore height on the health status and growth rate of farmed Pacific oyster *Crassostrea gigas* spat in Dungarvan Bay, Ireland	NUS
31	Bryan Wong Kang Ing	31-May-19 to 27-Jul-19	University College Cork	Ireland	Effect of the thermal influences from the warm summer of 2018 on native and invasive barnacles in Lough Hyne	NUS
32	Stephanie Toh Kay Wai	26-May-19 to 31-Jul-19	University of Hong Kong	Hong Kong	Sexual selection and its association with size-assortative mating and sexual size dimorphism in the intertidal gastropod *Nerita yoldii*	NUS
33	Tan Ke En	27-May-19 to 1-Aug-19	University of Hong Kong	Hong Kong	Spatial variation in thermal tolerance of the rocky intertidal snail *Nerita yoldii*	NUS
34	Jonathan Leo Guan Wei	22-May-19 to 31-Jul-19	University of Helsinki	Finland	Algal abundance is associated with macrophyte density in the Baltic Sea	NUS
35	Ng Ming Sheng	25-May-19 to 6-Jul-19	Prince of Songkla University Hat Yai	Thailand	Effects of warming on the interactions between seagrass, *Thalassia hemprichii*, and non-calcified and calcified macroalgae	NUS
36	Amanda Cheong	29-May-18 to 2-Jun-18	National Oceanography Centre of Southampton	UK	Quantifying dissolved organic matter and how the composition changes along a land-to-ocean continuum	NTU

S/N	Student name	Attachment period	Institution of attachment	Country of attachment	Project title	University
37	Eddy Kwoh Zhi Yan	23-Jun-19 to 28-Jul-19	Institute of Oceanography, National Taiwan University	Taiwan	Studying environmental impacts on zooplankton communities	NTU
38	Regine Tiong Hui Yi	10-Jun-19 to 9-Jul-19	University of Exeter	Cyprus (Northern Cyprus)	Marine turtle conservation project in Cyprus	NTU

Students who were funded by the Explore Programme

No.	Student name	Institution	Project title	Host supervisor	SJINML mentor	Date
1	Danial Mazlan	NTU-NIE	A comparative study of cellular and biochemical responses of intertidal gastropods at East Coast Park, Berlayer Creek, and St. John's Island to stress by heat and exposure	Dr Beverly Goh	Dr Jani TI Tanzil	Jan-18
2	Kelly Ng Hui Li	NUS	Imposex in muricid gastropods (Mollusca, Neogastropoda, Muricidae) in Singapore	Dr Tan Koh Siang	NA	Jan-18
3	Lim Siew Kin	Republic Polytechnic	Effect of heat stress on *Halophila ovalis*	Mr Steven Fong	Dr Ow Yan Xiang	Jan-18
4	Regan Chong	Republic Polytechnic	Effects of temperature and salinity on the survival and growth of three ecologically important snail species in Singapore decade after a worldwide ban of tributyltin use in antifouling paint	Dr Laura Yap	Dr Loo Poh Leong	Jan-18
5	Sirius Ng Zheng Hui	NUS	Assessment of dugong feeding trails in Singapore	Dr Zeehan Jaafar	Dr Ow Yan Xiang	Jan-18
6	Lim Xin Hui	RJC	The effect of particulate organic matter (POM) on coral trophic dynamics	Dr Abigayle Ng	Dr Jani TI Tanzil	Jan-18
7	Leon Sun Wai Loong	NTU-EOS/ ASE	Understanding the growth and physiology of *Heliopora coerulea* and its role as an iron sink in reef biogeochemistry	A/Prof Nathalie Goodkin	Dr Jani TI Tanzil	Jan-18
8	Foo Sze Hui	NUS	Assessing the identities of *Heterometra* spp. (Echinodermata: Crinoidea: Himerometridae) in Singapore based on morphology and molecular data	Asst Prof Huang Danwei	Dr Tan Koh Siang	Jan-18

No.	Student name	Institution	Project title	Host supervisor	SJINML mentor	Date
9	Wu Yuwei	NUS	Do native predators feed on the recently introduced American mussel *Mytella himerometridae* in Singapore based on morphology and molecular data strigata (Hanley, 1843) in Singapore?	Dr Tan Koh Siang	NA	Jan-18
10	Ling Jia Shin	NTU-ASE	Documenting the possible impacts of microplastic ingestion on hard corals	Asst Prof Janice Lee Ser Huay	Dr Jani TI Tanzil	Jun-18
11	Darren Wee Aik Jin	Nanyang Polytechnic	Developing a preliminary understanding of mud crab feed and dietary preferences	Dr Mark Richards	Dr Loo Poh Leong	Jun-18
12	Yusof Arshad s/o Yusof Mannan	James Cook University Singapore	The role of seagrass on fish assemblages in Singapore	Dr Neil Hutchinson	Dr Ow Yan Xiang	Apr-19
13	Tan Khay Yi Sarah	NTU-NIE	Elicidating the reproductive strategy of the Neptune's sponge, *Cliona patera*, in Singapore waters	Dr Beverly Goh	Mr Lim Swee Cheng	Apr-19
14	Low Yi Liang Kevin	NTU-Civil Engineering	Ecocement for restoration of coral reefs and coastal erosion control	Prof Chu Jian	Dr Jani TI Tanzil	Apr-19
15	Rae Chua	NTU-Biological Sciences	SIMPLE: Can the diversity of Singapore Marine Planktonic Eukaryotes be uncovered using culture methods?	Asst Prof Adriana Lopes dos Santos, ASE-NTU	Dr Maria Yung	Apr-19
16	Cham Soon Kiat Joseph	NUS	Factors influencing nesting in the hawksbill turtle, *Eretmochelys imbricata*, in Singapore	Dr Zeehan Jaafar	Dr Ow Yan Xiang	Apr-19
17	Lim Jia Yi Annabel	NUS	Isolation and characterisation of tyrosinases from marine sources	Dr Linda Sellou	Ms Serina Lee	Apr-19
18	Tan Kian Long	NUS	Effect of tyrosinase on marine mussel, ascidian, and brown algae fouling	Dr Linda Sellou	Ms Serina Lee	Apr-19
19	Goh Qiu Ting	Republic Polytechnic	Land-based production of *Caulerpa* species in aquaculture wastewater	Dr Grace Loo	Dr Loo Poh Leong	Apr-19
20	Chan Jia Qi Jaclyn	Republic Polytechnic	Symbiotic relationship between flatworms and corals	Dr Grace Loo	Dr Loo Poh Leong	Apr-19
21	Koh Shaojun Declan	NUS High School of Maths & Science	Methodologies for screening and documentation of micro-molluscs in intertidal and benthic communities around Singapore	Ms Valerie Lim (NUSHS), A/Prof Eric Yap (NTU)	Dr Tan Koh Siang & Ms Lim Lay Peng	Apr-19

No.	Student name	Institution	Project title	Host supervisor	SJINML mentor	Date
22	Nur Nadiah Bte Mohd Ikbar	NUS	Development of a tropical phytoplankton database using a FlowCam	Dr Leong Chee Yew	NA	Jul-19
23	Lim Jun An	NUS	Polychaete husbandry and suitability as feed for mud crabs	Dr Ng Ngan Kee	Drs Loo Poh Leong & Tan Koh Siang	Jul-19
24	Jurgen Lee Zheng Yi	NUS	Systematic assessment of fish larvae communities in Singapore	Dr Zeehan Jaafar	Dr Jani TI Tanzil	Jul-19
25	Kevin Leonardo	Republic Polytechnic	Feeding strategies of mangrove horseshoe crab, *Carcinoscorpius rotundicauda*	Dr Laura Yap	Dr Loo Poh Leong	Jul-19
26	Santo-Perry Rene wan ting	Republic Polytechnic	Population status and cultivation of two commercially exploited sea cucumbers in Singapore	Dr Laura Yap	Dr Neo Mei Lin	Jul-19
27	Ng Zheng Hui Sirius	Life Science, NUS	A multi-pronged approach to elucidating *Dugong dugon* foraging behaviour in Singapore	Dr Zeehan Jaafar	Dr Ow Yan Xiang	Jul-19
28	Marcus Yeo Yue Long	Millenia Institute	Special Project: Bivalves in seagrass meadows at Lazarus Island	Mr Foo Yong Kuan	Dr Tan Koh Siang & Ms Helen Wong	Jul-19
29	Randolph Daniel Palarca Vega	Millenia Institute	Special Project: Bivalves in seagrass meadows at Lazarus Island	Mr Foo Yong Kuan	Dr Tan Koh Siang & Ms Helen Wong	Jul-19
30	Amira Binti Mohamad Rafi	NUS	Spatial-temporal variations in the seagrass habitat of Bendera Bay at St. John’s Island	Dr Zeehan Jaafar	Dr Jani TI Tanzil	Jan-20
31	Ang Hao Yuan	NTU-NIE	Comparative study of abundance and distribution of echinoderms and baseline assessment of physiological biomarkers in suitable sea star species in inter-tidal areas at St. John’s Island and Lazarus Island	Dr Beverly Goh	Dr Jani TI Tanzil	Jan-20
32	Terry Tantio	NUS	Community composition of fishes in coastal habitats, Singapore	Dr Zeehan Jaafar	Dr Ow Yan Xiang	Jan-20
33	Bryan Wong Kang Ing	NUS	Investigating microbial communities of integrated multitrophic recirculating	Dr Ng Ngan Kee	Dr Loo Poh Leong	May-20

No.	Student name	Institution	Project title	Host supervisor	SJINML mentor	Date
34	Inez Yi-Ling Alsagoff	NUS	Fish predator assemblages in coral reefs using Baited Remote Underwater Video Systems (BRUVS)	Dr Zeehan Jaafar	Dr Jani TI Tanzil	May-20
35	Rachel Lau Yu San	NUS	Inorganic carbon burial potential of seagrass meadows alongside landscape consideration: A perspective from Singapore's southern coast	Dr Massimo Lupascu	Dr Ow Yan Xiang	May-20
36	Sarah Priyanka Nelson	NUS	Investigating ichthyoplankton communities in shallow coastal habitats of Singapore	Dr Zeehan Jaafar	Dr Jani TI Tanzil	May-20
37	Koh Zhiqi Shermaine	NUS	Evaluating plant-based supplements for in vitro cell culture of *Penaeus vannamei*	Dr Wu Jinlu	Dr Loo Poh Leong	May-20
38	Woo Bing Jun	NUS	Evaluating the invertebrate mesozooplankton in waters off Singapore's Southern Islands	Dr Maxine Allayne Darlene Mowe	Dr Jani TI Tanzil	May-20
39	Germaine Lim Kai Lin	Republic Polytechnic	Effects of elevated temperatures on the clearance rate of *T. crocea* fed at three microalgal densities	Ms Grace Loo	Dr Neo Mei Lin	May-20
40	Jerryl Tan Kim Han	Republic Polytechnic	Assessing suitability of waste-based micropellets for culturing juveniles of blood cockle *Anadara granosa* (Linnaeus)	Ms Grace Loo	Dr Loo Poh Leong	May-20
41	Yee Xin Yan	Republic Polytechnic	Short term impact of hypo-salinity on tropical seagrass species	Ms Grace Loo	Dr Ow Yan Xiang	May-20
42	Mathias Luk Wan Kai	St Andrew's Junior College	Effects of heat stress on the the anemone *Isactinia citrina*: Preliminary study on bleaching susceptibility and recovery patterns	Ms Rinie Gupta	Drs Jani TI Tanzil & Nicholas WL Yap	May-20
43	Chew Ming En Lucas	Temasek Polytechnic	Ocean acidification matters: The effect of low pH on the reproductive success and larvae development of giant clam *Tridacna crocea*	Dr Cynthia Wong	Dr Neo Mei Lin	May-20
44	Sheena Heng Siew Weng	Temasek Polytechnic	Coral heterotrophy: Effects on supplementary feeding on the recovery rates of hermatypic corals from thermal bleaching stress	Dr Cynthia Wong	Dr Jani TI Tanzil	May-20

PhD students trained under the MSRDP

The format follows: Name; MSRDP project association

1. Thio Si Kuan; P1
2. Fu Jing Jan; P1
3. Ryan de Sotto; P1
4. Cheah Hee; P1
5. Randolph Quek Zheng Bin; P3
6. Samuel Chan Yong Kit; P3
7. Jenny Fong; P3
8. Aaron Teo Yi Sheng; P3
9. Peggy Tang Pei Yi; P3
10. Daisuke Taira; P5
11. Amanda Lim Yue Han; P5
12. Yeo Hui Jing Hannah; P5
13. Yip Yong Jie; P7
14. Samarth Bhargava; P7
15. Robert Nichols; P11
16. Molly Moynihan; P11
17. Rosalie Chai Mei Yi; P12
18. Prasanna Jogdeo; P12
19. Yuan Yee Phan; P12
20. Christaline George; P13
21. Sandra Kolundzija; P13
22. Pang Li Mei; P15
23. Gary Ding Chi Ying; P15
24. Ma Yadanar Phyo; P15
25. Boo Mel Veen; P22
26. Tan Boon Teoh; P28
27. Andrei Lebedev; P28
28. Kostiantyn Sopiha; P28
29. Ihor Radchenko; P28
30. Puwakdandawke Vishakha Thilini Weerassinghe; P28
31. Zhang Rui; P28
32. Yongli Zhou; P32
33. Yuan Chen; P32
34. Zaara Yadanar Phyo; P34
35. Nicholas Yap Wei Liang; P38

Master's students trained under the MSRDP

The format follows: Student's name; MSRDP project association

1. Chuang Li Ching Elaine; P1
2. Jain Sudhanshi Sanjeev; P3
3. Marshall Ong Ji Fa; P15
4. Goh Hui Chin; P15
5. Goh Jun Xian; P15
6. Muhammad Zulfaqar Bin Ali; P15
7. Ho Xin Yi; P15
8. Farhan bin Aidil; P15
9. Shelley Chan Hiang Ming; P5
10. Ying Shu Min, Lynette; P5
11. Li Haonan; P7
12. A.J.M Hasanthi Lakshika Senevirathna; P28
13. Kim Jaejung; P34

MSRDP outreach events and activities

1. 11 Jun 2021: Young Marine Scientist Symposium
2. 13 Jan 2021: SG Biodiversity special, organised by Channel NewsAsia demonstrating how eco-engineering can help in conservation
3. 21 Jun 2020: International Webinar of Asian Horseshoe Crab Conservation 2020
4. 19 Jun 2020: International Symposium on Current Research on Asian Horseshoe Crabs in conjunction with the first International Horseshoe Crab Day
5. 26 May 2020: Talk by Stephen Summers on 'Engineered seawalls: How does seawall material influence their biofilm', as part of the SingJams Microbiology Seminar Series, Singapore
6. 21 Jan 2020: Public seminar on 'Phase-resolved numerical simulation of nonlinear random waves on large scale' by Jinghua Wang, research fellow in the Department of Civil and Environmental Engineering
7. 9–10 Jan 2020: Republic Polytechnic Open House showcasing the horseshoe crab project to the public, explaining the tagging equipment and relevance to the project
8. 9 Jan 2020: Public seminar on 'Effects of flexible coastal vegetation on waves in water of intermediate depth' by Jie Hu, PhD candidate in the Department of Civil and Environmental Engineering at NUS
9. 28 Nov 2019: Lecture given to 43 Republic Polytechnic students on wildlife ecology and conservation of horseshoe crabs
10. 24 Oct 2019: Talk on developing an integrated database for marine science, MeTIS, by Ooi SK
11. 22 Oct 2019: MSRDP Harmful Algal Bloom Workshop for 26 participants from School of Science and Technology, Singapore, by Christina Chai and Sandric Leong
12. 21 Oct 2019: Fireside chat: 'Can Plastics to Fuel Technology mitigate the plastics waste problem?' In collaboration with RVRC (NUS), Coca-Cola, GA Circular and Engco; 40 participants
13. 18 Oct 2019: Public seminar on machine learning and neural networks by Heng Xiao, assistant professor in the Department of Aerospace and Ocean Engineering at Virginia Tech
14. 17 Oct 2019: Public seminar on 'Turbulence modelling in the age of data: From data assimilation to machine learning' by Heng Xiao, assistant professor in the Department of Aerospace and Ocean Engineering at Virginia Tech

15. 9 Oct 2019: Public seminar on 'Circular port construction in Singapore: Making "unsuitables" suitable in Tuas Terminal Phase II' by Jamie Lescinski, senior engineering manager at Boskalis
16. 28 Sep 2019: Approximately 70 beneficiaries from Woodlands Social Centre, Pacific Activity Centre, and Anglican Senior Centre learnt about horseshoe crab conservation
17. 24 Sep 2019: Public seminar on 'Using porous layers as a passive motion damping system for floating wind turbine platforms' by Anna Feichtner, PhD student at the University of Exeter
18. 14 Sep 2019: A*STAR and the Singapore Science Centre's Xperiment! @ One North Festival
19. 30 Aug 2019: Public seminar on 'Numerical modelling on the development of 3D local scours under the interaction between wave, current, and structures' by Tso-Ren Wu, Associate Vice President for International Affairs and Associate Professor at the National Central University (Taiwan)
20. 23 Aug 2019: Public seminar on air-water flow in hydraulic engineering by David Zhu, professor at the University of Alberta
21. 2, 16, 23, 29 Aug 2019: Lee Kong Chian Natural History Museum and St. John's Island National Marine Laboratory's Marine Conservation Programme, Marine Exploration Day Camps
22. 30 Jul 2019: Seakeepers Educational Outreach Programme, Nan Hua Secondary School—Coral research and promoting conservation in Singapore
23. 29 Jun 2019: Young Marine Scientist Symposium (150 pax), including presentation by Yip Yong Jie on 'Retention and toxicity of nanoplastics particles in marine invertebrate larvae: A study using planktonic larvae of *Amphibalanus amphrite* and *Spirobranchus sp*'
24. 29 Jun 2019: Talk on 'Enhancing our coastal defence structures through coral transplantation' at the Young Marine Scientist Symposium
25. 14 Jun 2019: Public seminar on 'Approaches to coastal design in remote locations: Zero maintenance designs and hand-built protection works' by Tom Shand, consultant from Tonkin + Taylor and senior lecturer at the University of Auckland
26. 5 Jun 2019: Marine science and thermodynamics workshop
27. 9 May 2019: Public seminar on 'Interaction of periodic waves with floating vegetation' by Jiang Yun, NUS
28. 12–13 Apr 2019: Horseshoe crab booth at the Asia Dive Expo to raise awareness about horseshoe crab conservation. Estimated 200 pax visited the booth
29. 12 Apr 2019: Teh Tarik Talk with Chen Tsuhan, Deputy President (Research and Technology), on coral transplantation
30. 4 Apr 2019: Public seminar on 'Nonlinear wave forcing and scattering on a fixed FPSO-shaped body driven by phase-focused wave groups' by Chen Hao, NUS
31. 21 Mar 2019: Public seminar on 'Artificial shorelines creating oases in an intertidal desert' by Gray Williams, The Swire Institute of Marine Science and School of Biological Sciences, The University of Hong Kong
32. 21 Mar 2019: Public seminar on 'The future of a monsoonal tropical marine ecosystem under climate change' by Bayden Russell, The Swire Institute of Marine Science and School of Biological Sciences, The University of Hong Kong
33. 16 Mar 2019: Celebrating Singapore Shores at Berlayar Creek
34. 12 Mar 2019: Sharing at Kranji Secondary School on the MSRDP-P19 project and need for conservation efforts of the horseshoe crab to 50 students
35. 9 Mar 2019: Talk on 'Global warming and recurrent mass bleaching of corals' by Andrew H Baird, James Cook University
36. 8 Mar 2019: 'Fate and toxicology of micro- and nanoplastics in real world scenarios' by Ana Isabel Catarino, Heriot-Watt University, Edinburgh, United Kingdom
37. 7 Mar 2019: Public seminar on 'Nonlinear analysis of bore-shaped waves from wave-flume experiments' by Sebastian Ujvary, Technische Universität Braunschweig
38. 1 Mar 2019: Marine Plastics Workshop conducted for 30 students from School of Science and Technology, Singapore (SST) at SJINML
39. 23–28 Feb 2019: Biodiversity of coral reefs and coral nursery at Pulau Bawah, Indonesia
40. 21 Feb 2019: MSRDP Mid-Term Symposium
41. 11 Feb 2019: 'Paradise trashed: Sources and solutions to marine litter issue in French Polynesia' by Scott Wilson, Macquarie University, Department of Environmental Sciences, Macquarie, NSW, Australia
42. 31 Jan 2019: Lunch talk on 'Murky reefs are the past and the future in the Coral Triangle' by Nadia Santodomingo and Ken Johnson, Natural History Museum, London, UK
43. 10–12 Jan 2019: Republic Polytechnic Open House showcasing our horseshoe crab project to the public, explaining the tagging equipment and relevance to our project
44. 11 Dec 2018: 'Microplastic debris in deep-sea canyon, estuarine, and shoreline sediments' by Ellie Jones, University of Oregon, USA
45. 5–6 Dec 2018: Public seminar on 'Holo-Hilbert spectral analysis' and 'On the degree of nonlinearity' by Norden E Huang, Innovation Center and Data Analysis Laboratory of the Center for Nonlinear Sciences (QNLMST), Qingdao, China
46. 5–7 Dec 2018: International Conference for Plastics in Marine Environment
47. 5 Dec 2018: SG-UK workshop organised on behalf of NRF and British High Commission
48. 4 Dec 2018: 'Perspectives from the Canadian Environmental Microplastics Facility' by Rhiannon Moore, OceanWise Canada

49. 28–29 Nov 2018: Marine Conservation in Southeast Asia Workshop
50. 21 Nov 2018: Lecture on wildlife ecology and conservation of horseshoe crabs at Republic Polytechnic
51. 12 Nov 2018: Raffles Girls' Primary School Career Fair booth on 'How to become a marine scientist'
52. 24 Oct 2018: Careers talk on 'Marine habitats and threats in Singapore' by L. S. M. Ying, P. Shantti for Meridian Primary School, Singapore
53. 8 Oct–2 Nov 2018: Internship programme for Cedar Girls' Gap Month 2018. Mentorship of interns, Chelsea Ku and Carina Ysha Paqueo Cangco, with the processing of reef cores. Mentors: Ambert Ang and Samuel Chan
54. 6 Oct 2018: 11th Anniversary Eco-Exhibition & Coral Garden exhibition booth where VIPs and guests learnt about coral gardening and coral transplantation on seawalls from Toh Tai Chong, Kikuzawa, and Lee Yen Ling
55. 27 Sep 2018: 'The big problem of microplastics' with guest panelist Neo Mei Lin, organised by Wildtype Media Group and City Development Limited
56. 9 Sep 2018: Videography for Student Learning Space (SLS), using data-loggers for coral research at SJINML, TMSI
57. 28 Aug 2018: Talk on 'Makassar Strait Throughflow, 2004–2017' by Arnold L Gordon
58. 23 Aug 2018: Seakeepers Educational Outreach Programme, Changkat Changi Secondary School—Coral research and promoting conservation in Singapore
59. 25 Jul 2018: Talk by Richard Thompson on 'Marine litter: Are there solutions to this global environmental problem?'
60. 16 Jul 2018: Talk by Ruth Thurstan on 'A blast from the past: Using historical approaches to explore long-term changes in marine fisheries'
61. 2–3 Jun 2018: Booth on conservation of horseshoe crabs at Festival of Biodiversity
62. 1 Jun 2018: Talk by Oren Levy on 'Cnidarians: Eat, Pray, Love'
63. 31 May 2018: Public seminar on 'Developments in tsunami hydrodynamics 2011–2018' by Costas Synolakis, University of Southern California
64. 25 May 2018: Booth on consequences of plastic pollution on horseshoe crab habitats at World Oceans Day, S.E.A. Aquarium
65. 14 May 2018: Talk on 'Corals as natural archives of the past' by Jani Tanzil at Pint of Science Singapore
66. 8 May 2018: Public seminar on 'Recent advance of deriving vegetation drag coefficient and modelling wave-vegetation interaction' by Zhan Hu, the Institute of Estuarine and Coastal Research, School of Marine Science, Sun Yat-sen University (SYSU)
67. 27 Apr 2018: Talk by Lawrence Liao, Hiroshima University
68. 26 Apr 2018: Public seminar on 'Inferences of tsunami characteristics from deposits' by Robert Weiss, from VPI (Virginia Tech)
69. 22 Apr 2018: Booth on conservation of horseshoe crabs at the Family Aqua Carnival
70. 6–9 Apr 2018: Booth on conservation of horseshoe crabs at the Asia Dive Expo 2018
71. 4 Apr 2018: Sharing by Sudhanshi Jain on marine science at KK Women's and Children's Hospital; about 50 visitors
72. 27 Mar 2018: RP's talk at Kranji Secondary School, which included sharing of the MSRDP-P19 project on conservation efforts of the horseshoe crab for 70 students
73. 24 Mar 2018: Sustainable Blue Spaces
74. 17–18 Mar 2018: The Fun Odyssea, International Year of the Reef 2018 Community Launch Event
75. 17 Mar 2018: Activity and information booth on marine chemistry, jointly with the groups of Patrick Martin, Adam Switzer, and Nathalie Goodkin
76. 13 Mar 2018: Talk on 'Marine ecosystems and climate change in Southeast Asia' by Huang Danwei at Climate Change and Law of the Sea
77. 10 Mar 2018: Talk on 'Corals as natural archives of the past' by Jani Tanzil at Marine Open House, LKCNHM
78. 9 Mar 2018: Two invited guest lectures by Lucinda Doyle at the Tanglin Trust School for International Baccalaureate and 'A' level students on High Pressure Microbiology
79. 2 Mar 2018: Intertidal guiding at Pulau Hantu for undergraduate students
80. 26 Feb 2018: Exxon-Mobil workshop for NTU researchers and Exxon-Mobil team leaders on 'Microbially influenced corrosion and biofouling' by Scott Rice
81. 13 Feb 2018: Talk on 'Innovation in biological interfaces for emerging industrial and health challenges'
82. 8–9 Feb 2018: Marine enrichment lecture and activity at Anglo-Chinese Junior College's Science and Math Council recruitment event
83. 2 Feb 2018: Public seminar on 'Surf and Swash flows generated by Transient Long Waves' by Ignacio Barranco, NUS
84. 2 Feb 2018: 'Beyond the water's edge', a TEDx talk at United World Colleges Dover by Elizabeth Heery, NUS
85. 2 Feb 2018: 'Floating classroom' session, a programme by Seakeepers Asia, where students learn about marine biodiversity aboard vessels
86. 1 Feb 2018: Intertidal guiding at St. John's Island (Sisters' Islands Marine Park) for undergraduate students
87. 30 Jan 2018: Public seminar on 'Climate change impacts on Chicago Urban Heat Island: Dynamical downscaling to pedestrian and building scales' by Patrick Conry, University of Notre Dame
88. 26 Jan 2018: 'Floating classroom' session, a programme by Seakeepers Asia, where students learn about marine biodiversity aboard vessels
89. 19 Jan 2018: Talk on 'Improvement of prevention and response capability against tsunami' by Taro Arikawa, Chuo University

90. 4–6 Jan 2018: Sharing with the public at the Republic Polytechnic Open House on how RP-DMAC is playing a part in horseshoe crab conservation efforts through its MSRDP-P19 project and what they have learnt
91. 17 Dec 2017: Talk on 'Exploring the roles of microbial communities in the marine environment' by Scott Rice at the SJINML Anniversary held at St. John's Island
92. 12 Dec 2017: Talk on 'The role of microbes in coral reef health and disease processes' by David Bourne, James Cook University
93. 27–29 Nov 2017: 1st Singapore–Hong Kong Hard Shore Ecology Workshop
94. 16 Nov 2017: Talk on 'Quest for the Ruby Seadragon' by Greg Rouse, Scripps Institution of Oceanography
95. 31 Oct 2017: 'Floating classroom' session, a programme by Seakeepers Asia, where students learn about marine biodiversity aboard vessels
96. 26 Oct 2017: WWF-Singapore's Brown Bag Lunch by Neo Mei Lin on 'Marine conservation in urban Singapore', organised by World Wildlife Fund, Singapore
97. 19 Oct 2017: Talk on 'Plastics in our environment' by Suresh Valiyaveetil, NUS
98. 13 Oct 2017: Seminar presentation for students from Greenview Secondary School; 'To sea or not to sea squirt' by Serina Lee, organised by SJINML Outreach
99. 19–24 Sep 2017: Visit to National Museum of Marine Biology and Aquarium, Taiwan, by Loo Poh Leong and Lee Yen-ling
100. 14 Sep 2017: Talk on 'Eco-engineering: design with nature' by Louise Firth, Plymouth University
101. 29 Aug 2017: SustainABLE NUS Showcase 2017
102. 24 Aug 2017: Talk on 'Numerical modelling for coastal and offshore developments' by Stefan Leschka, DHI
103. 22 Aug 2017: Talk on 'Waves and wave-driven flow over reefs' by Stephen Monismith, Stanford
104. 11 Aug 2017: Talk on 'The future of the oceans' by Patrick Martin, NTU
105. 20 Jul 2017: 'Impacts of climate change on biological systems' by Huang Danwei at the NJC Bio-Geog Inter-Disciplinary Seminar on Climate Change, seminar hosted by National Junior College
106. 7 Jul 2017: Talk on 'Natural history of the Kimberley coral reefs' by Giada Bufarale, Curtin University
107. 5–7 Jul 2017: Cnidarian Culture Workshop (sessions by Lee Yen-ling)
108. 29 Jun 2017: Talk on 'ReefBudget: A census-based evaluation of coral reef carbonate budgets' by Fraser Januchowski-Hartley, MARBEC
109. 27–28 May 2017: Craft workshop at the Festival of Biodiversity
110. 18 May 2017: Talk at the Canadian International School by Peter Todd, NUS
111. 1 Apr 2017: Intertidal guiding at Sisters' Island for undergraduate students
112. 18 Mar 2017: Talk by Neo Mei Lin on marine conservation in Singapore at the Marine Open House @ Lee Kong Chian Natural History Museum
113. 11 Mar 2017: Talk at NUS Open Day by Peter Todd, NUS
114. 23 Jan 2017: Talk on 'Evolution of vortex structure from separated boundary layer during run-down motion of solitary wave propagating over very steep beach' by Cheng Lin, National Chung Hsing University
115. 7 Dec 2016: Talk on 'Conserving marine biodiversity through the lens of evolutionary and ecological history' by Huang Danwei at iDiv, German Centre for Integrative Biodiversity Research
116. 16 Nov 2016: International Workshop on Eco-shoreline Designs for Sustainable Coastal Development

Selected MSRDP-related media coverage

1. 4 Apr 2021. Channel NewsAsia: Midnight Story
2. 7 Nov 2019. ZB Online: 国大研发新智能手机仪器可快速检测有害海藻
3. 7 Nov 2019. The Straits Times: NUS team's device detects algae quickly
4. 6 Nov 2019. The Straits Times: Device developed by NUS engineers uses smartphone to detect harmful algae in minutes
5. 6 Nov 2019. Channel NewsAsia: Smartphone-based gadget to help detect toxic algae in water
6. 6 Nov 2019. Berita Mediacorp: Jurutera NUS hasilkan peranti baru; berupaya tentukan kandungan lumut dalam air dengan mudah dan pantas
7. 6 Nov 2019. The Engineer: Smartphone sensor takes minutes to detect harmful algae
8. 6 Nov 2019. New Atlas: Smartphone system quickly detects harmful algae in water
9. 6 Nov 2019. Tech Explorist: Smartphone device that detects harmful algae in 15 minutes
10. 17 Sep 2019. NUS News: "Naked" corals of Singapore
11. 29 Jun 2019. The Straits Times: Most coral species in Singapore resilient to projected rise in sea levels
12. 31 May 2018. NUS News: Nanoplastics found to accumulate in marine organisms, risk being transferred up food chain: NUS study
13. 31 May 2018. Channel NewsAsia: Nanoplastics accumulate in marine organisms and may pose harm to aquatic food chains
14. 31 May 2018. The Straits Times: Nanoplastics can accumulate in marine organisms' bodies, NUS research finds
15. 31 May 2018. Today: Nanoplastics can accumulate in marine life and threaten human health: NUS study

16. 31 May 2018. Tech Explorist: Nanoplastics accumulate in marine organisms and may pose harm to aquatic food chains
17. 31 May 2018. Science Newsline: Nanoplastics accumulate in marine organisms and may pose harm to aquatic food chains
18. Dec 2017. Advances in Science: Why history matters
19. Dec 2017. Advances in Science: Greening Singapore's seawalls
20. 29 Nov 2016. NUS News: Marine lab opens to all
21. 29 Nov 2016. The Straits Times: 7 marine science projects get funding
22. 29 Nov 2016. Today: 7 research projects awarded under marine science R&D programme
23. 29 Nov 2016. 联合早报: 七项海洋科研获资助 对抗红潮方法料三年内找到
24. 29 Nov 2016. Berita Harian: Tujuh projek sains marin kaji daya tahan terumbu karang, pertumbuhan alga
25. 29 Nov 2016. Tamil Murasu: New research projects to study algae blooms, how coral reefs adapt to environmental change
26. 28 Nov 2016. The Straits Times: New research projects to study algae blooms, how coral reefs adapt to environmental change
27. 28 Nov 2016. 联合早报: 政府资助七海洋科学研究推动海洋科研发展
28. 28 Nov 2016. Channel 8 News: 张志贤：研究基金会拨款 助7海洋科研项目
29. 28 Nov 2016. Suria News: 7 projek kajian marin dapat suntikan dana di bawah program R&D
30. 28 Nov 2016 Vasantham News: கடல்சார் அறிவியல் - 7 ஆய்வுத் திட்டங்களுக்குக்கு உதவி
31. 28 Nov 2016. Venture Capital Post: R&D programme awarded with 7 marine research projects
32. 1 Jul 2016. The Straits Times: Giving marine pests the slip
33. 30 Jun 2016. The Straits Times: New $25m programme for marine science research and development in Singapore

International institutional and industrial relationships established

International institutions of higher learning and industrial partners	Collaborators
Adaptive Surface Technologies Inc, USA	Dr Kim Philseok [MSRDP-P29] Dr Teluka Galhenage [MSRDP-P29]
American Natural History Museum, USA	A/Prof Nathalie Goodkin [MSRDP-P03 & MSRDP-P11]
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Burapha University, Thailand	Dr Kitithorn Sanpanich [MSRDP-P25]
Curtin University, Australia	Dr Nicola Browne [MSRDP-P03]
Department of Zoology, Myeik University, Myanmar	Dr Wah Wah Min [MSRDP-P41]
Engco Pte Ltd, Singapore	-
Exxon-Mobil	-
GA Circular	-
Hebrew University of Jeruseleum, Israel	Dr Debbie Lindell [MSRDP-P13]
Heriott-Watt University, UK	Prof Alex Poulton [MSRDP-P32]

International institutions of higher learning and industrial partners	Collaborators
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Institut de la corrosion, France	Prof Dominique Thierry [MSRDP-P12]
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Institute of Marine Sciences, University of Chittagong, Bangladesh	Dr Mohammad Eusuf Hasan [MSRDP-P41]
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James Cook University, Australia	Prof Andrew S Hoey [MSRDP-P03]
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Norwegian Research Centre, Norway	Dr Richard Sanders [MSRDP-P32]
NRF-British High Commission	-
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University of Plymouth, UK	Dr Louise Firth [MSRDP-P05]
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San Diego State University, USA	Dr Park Sungyong [MSRDP-P01]

International institutions of higher learning and industrial partners	Collaborators
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Swire Institute of Marine Science, Hong Kong	Prof Gray Williams [MSRDP-P05]
The Coca-Cola Company	-
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