FOUNDATIONAL RESEARCH CAPABILITIES SMALL STUDY REPORT ON

MARINE SCIENCE AND OCEANOGRAPHY

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EXECUTIVE SUMMARY

- As a small island nation, Singapore faces increasing pressures on its marine environment to meet societal needs, including water, food and energy security, intensifying human activities, as well as climate change mitigation and adaptation. In particular, there are ongoing plans for the expansion of its aquaculture industry, diversification of recreational activities, and engineering of coastal defences against sea-level rise. **Proactive planning and integrated management of her coastlines, guided by the best available science and data, are vital to the nation's need for sustainable growth and long-term resilience.**
- Fortunately, Singapore's marine environment is one of the most extensively studied globally, with a long history of data collection, monitoring and research across biological, chemical, and physical oceanographic disciplines. There have been longstanding research efforts to assess and manage the environmental impacts of Singapore's rapid and extensive coastal development since its independence in 1965. In fact, **Singapore has a strong foundation for marine science underpinned by at least two centuries of baseline studies.**
- A recent example of such an effort is the Marine Science R&D Programme (MSRDP; 2015-2021), supported by Singapore's National Research Foundation (NRF). The MSRDP coordinated research across Institutes of Higher Learning (IHLs) with the goal of addressing specific knowledge gaps on Singapore's coastal and marine ecosystems, mitigating ongoing environmental threats, and developing targeted solutions. **The MSRDP has all the hallmarks of a successful multi-stakeholder and multidisciplinary marine science programme in terms of research, capacity building and science communications.** It produced over 200 high-quality peer-reviewed publications, and trained 119 research scientists and engineers, as well as 35 PhD, 16 MSc and 51 polytechnic students. Over 75% of these researchers are now embedded in various local and international institutions and industries.
- In the decades ahead, the twin crises of climate change and biodiversity loss are the biggest challenges facing coastal and marine ecosystems in Singapore and Southeast Asia. Given that Singapore is inextricably linked to the region in myriad ways – biophysically, ecologically, geopolitically, socioeconomically and culturally, **it would be near impossible to fully understand, and much less tackle, Singapore's marine environmental challenges without a firm grasp of the regional context, data and science**. As an island nation, Singapore should continue to contribute to regional and international marine science and policy studies including the high seas treaty, deep sea exploration and polar research by strengthening and expanding its network of collaborations.
- Given the uncertain trajectories of climate and environmental change in the region, Singapore should **invest in marine science research that both addresses immediate operational needs – the "known knowns" and "known unknowns" (e.g. environmental impacts of near-shore oil spills), as well as help policymakers respond to unanticipated risks, challenges and opportunities – the "unknown unknowns" (e.g. resilience to long-term climate disturbances).** Providing space for researchers to explore both applied and blue-skies research will expand our toolbox of solutions, uncover blind spots and create enabling conditions for groundbreaking discoveries with transformative impacts. Discovery-driven research also fosters a culture of inquiry and creativity, which helps attract and retain top talent for marine science in Singapore.

- **As Singapore and the region's marine environmental challenges become increasingly complex – crossing disciplines, sectors, geographies and national boundaries, so too must be the research and development of new knowledge, technologies and solutions to address them.** Notably, the conservation of mangrove forests and other blue carbon ecosystems has the potential to benefit climate, biodiversity and local communities, but requires close and effective collaborations between scientists, economists, governments, businesses and civil society.
- Given the diverse interests and priorities of stakeholders for marine science in Singapore and the region, **we recommend the establishment of a National Initiative for Marine and Ocean Sciences (NIMOS), comprising a consortium of IHLs, research institutes and government agencies, to achieve strategic scientific alignment, build capacity and deep expertise, and create long-lasting policy impacts** for marine environmental sustainability and resilience in Singapore and the region. We recommend that NIMOS prioritise marine science and oceanographic research in the following verticals and horizontals (Figure 1):
    - Verticals: (1) **Biodiversity & Nature**, to establish baselines and improve fundamental knowledge of the functioning of marine ecosystems; (2) **Environment & Climate**, to determine environmental limits and characterise key ocean processes vital for safeguarding ocean and human health under climate change; and (3) **Ecosystem Resilience**, to develop adaptation strategies to retain, rejuvenate and restore key ecosystem functions and services.
    - Horizontals: (1) **Marine Technologies**, for the design and broad implementation of innovative and technology-driven solutions; (2) **Marine Policy, Governance & Law**, to produce a science-based framework to support environmental management and decision-making associated with the utilisation of Singapore's sea space; and (3) **Ocean Literacy**, to improve the public's engagement and understanding of marine science, risks and opportunities.
- Importantly, to inform and future-proof Singapore's policies, strategies and actions for marine environmental sustainability and resilience, it will be important for NIMOS to **invest in foundational marine research capabilities that achieve delicate balances between being Singapore-centric *and* region-relevant, being use-inspired *and* discovery-driven, and being domain-specialised *and* cross-disciplinary.**
- We recommend that NIMOS be hosted at IHL(s) in close partnership with government agencies and research infrastructures such as St John's Island National Marine Laboratory (SJINML). The IHL(s) would serve as NIMOS' secretariat and house a core team of Singapore-based world-class marine scientists pursuing the abovementioned research priorities. **NIMOS would adopt a hub-and-spoke model, whereby existing and future national and international marine research institutes, programmes and initiatives could plug in as key partners and stakeholders (Figure 1).**
- Currently, no such marine science network exists in Singapore, Southeast Asia or under the ASEAN framework. **NIMOS fills this gap by serving as a research hub and coordinating platform to strengthen our local and regional linkages, engender greater opportunities for international research collaboration, and translate research to actions for the benefit of coastal and marine ecosystems and communities in Singapore and beyond.**

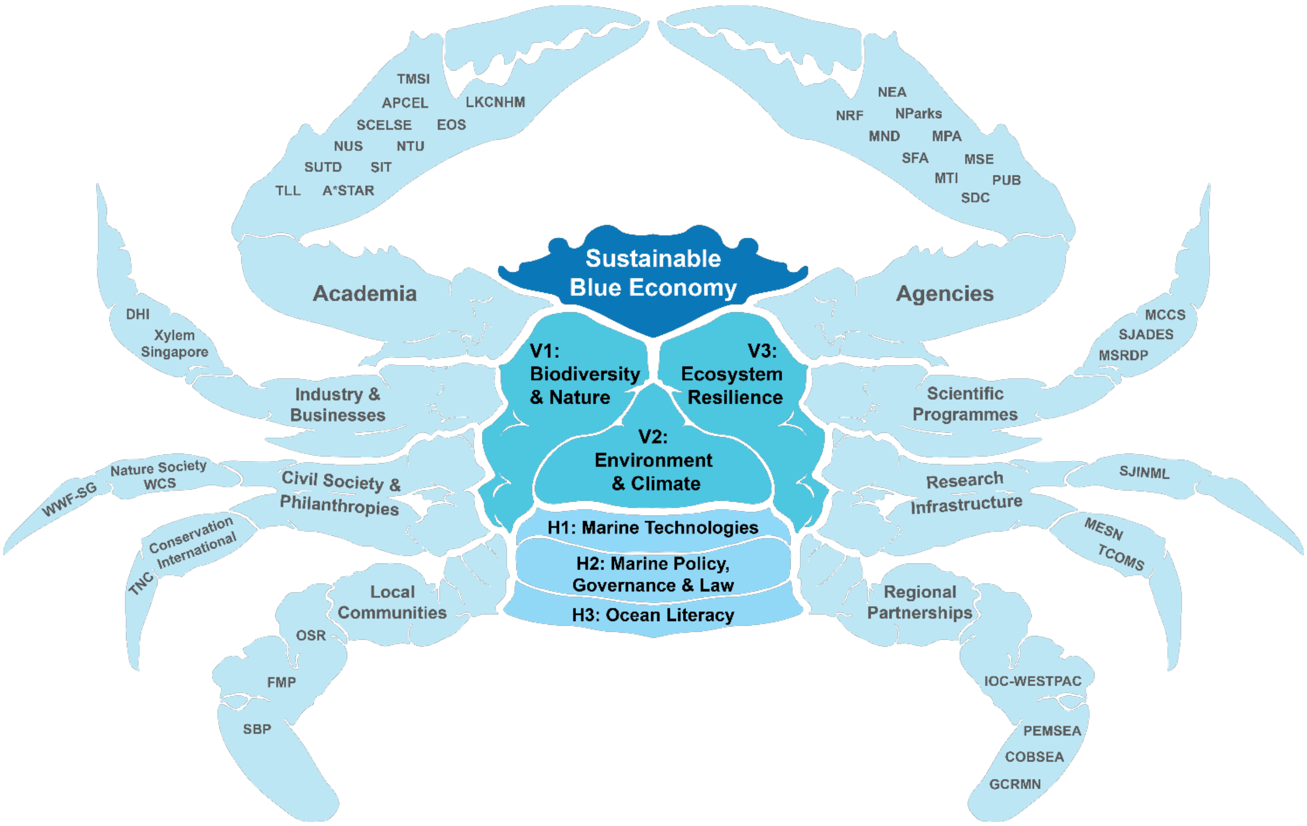

Figure 1. The proposed National Initiative for Marine and Ocean Sciences (NIMOS) to achieve a sustainable blue economy, with research delivered through three cross-cutting verticals, supported by three horizontals. NIMOS will enable academia to work in close partnership with government agencies and research infrastructure. It will adopt a hub-and-spoke model, whereby existing and future national and international research institutes, programmes, initiatives and other stakeholders would plug into NIMOS as key partners. NIMOS will create the enabling conditions to strengthen our local and regional linkages, engender greater opportunities for international research collaboration, and translate research to actions. The non-exhaustive list of key stakeholders include academia: Agency for Science, Technology and Research (A*STAR), Asia-Pacific Centre for Environmental Law (APCEL), Earth Observatory of Singapore (EOS), Lee Kong Chian Natural History Museum (LKCNHM), National University of Singapore (NUS), Nanyang Technological University (NTU), Singapore Centre for Environmental Life Sciences Engineering (SCELSE), Singapore Institute of Technology (SIT), Singapore University of Technology and Design (SUTD), Temasek Life Sciences Laboratory (TLL), Tropical Marine Science Institute (TMSI); government ministries and agencies: Ministry of National Development (MND), Maritime and Port Authority (MPA), Ministry of Sustainability and the Environment (MSE), Ministry of Trade and Industry, Singapore (MTI), National Environment Agency (NEA), National Parks Board (NParks), National Research Foundation (NRF), Public Utilities Board (PUB), Sentosa Development Corporation (SDC), Singapore Food Agency (SFA); scientific programmes: Marine Climate Change Science (MCCS), Marine Science Research and Development Programme (MSRDP), South Java Deep-Sea (SJADES) Biodiversity Expedition; research infrastructure: Marine Environment Sensing Network (MESN), St John's Island National Marine Laboratory (SJINML), Technology Centre for Offshore and Marine, Singapore (TCOMS); regional partnerships: Coordinating Body on the Seas of East Asia (COBSEA), Global Coral Reef Monitoring Network (GCRMN), Intergovernmental Oceanographic Commission Sub-Commission for the Western Pacific (IOC-WESTPAC), Partnerships in Environmental Management for the Seas of East Asia (PEMSEA); local communities: Friends of the Marine Park (FMP), Our Singapore Reefs (OSR), Singapore Blue Plan (SBP); civil society and philanthropies: Conservation International, Nature Society (Singapore), The Nature Conservancy (TNC), Wildlife Conservation Society (WCS), World Wildlife Fund (WWF-SG); industry and businesses: DHI Water & Environment (S) Pte Ltd, Xylem Singapore.

INTRODUCTION

Since independence, Singapore has developed rapidly to address the living needs of a young city state. As a port city, this involves massive urban development and land reclamation of the coastal zone to meet a plethora of socioeconomic demands including water, food and energy. As demand for the shrinking sea space continues to grow, it is vital to leverage the best science to integrate these uses so that the coastal and marine areas can continue to function optimally and drive socioeconomic progress (Figure 2).

Figure 2. The coastlines of Singapore are dominated by rich marine habitats, such as coral reefs and seagrass meadows. These natural assets thrive alongside urbanisation and increasing demand by numerous stakeholders.

At the global level, the United Nations adopted as part of the 2030 Agenda for Sustainable Development a set of 17 Sustainable Development Goals (SDGs), committing attention and resources to secure a sustainable planet for humanity. The SDG 14, or 'Life below water', calls for nations to conserve and utilise resources in the marine environment sustainably [1]. At the same time, the Singapore Government is aiming to transform Singapore into a sustainable and resilient *City in Nature* as part of its Green Plan 2030 [2]. This national blueprint sets forth long-term goals and strategies to address critical issues of climate change, biodiversity loss, and resource sustainability across all sectors, including the coastal and marine areas. To this end, Singapore is expanding its network of nature parks and strengthening ecological connectivity. Specifically, a second marine park will be established at the southern islands, driven by the need to strengthen recruitment of biodiversity in the existing marine park network [3,4]. Concurrently, there are ongoing plans for the expansion and transformation of Singapore's maritime and marine aquaculture industries, re-engineering of coastal defences, and diversifying recreation—all to coexist in the same seascape. Proactive planning and integrated management of such multifaceted uses of our marine assets have never been more vital to Singapore's ambitions for sustainable development and to seize opportunities with rising environmental challenges.

However, the complex nature of coastal waters caused by the evolving coastline and dynamic processes—across natural and man-made assets linked to local and regional drivers—requires that scientific data and knowledge need to be integrated across diverse scientific disciplines to promote functional marine habitats for sustaining environmental processes and provide key ecosystem services. There is also growing need to strengthen our knowledge of the state of the regional seas. Regional water mixing play a vital role in regulating Singapore's marine environment—determining not only the baseline quality of water flushing into Singapore, but also regulating effects of climate change in the region [5–7]. This understanding is needed to improve Singapore's capacity for pre-emptive environmental management of both local and regional marine resources, enabling sustainable use of the surrounding transboundary sea space and conservation of ASEAN's interconnected ecosystems. Importantly, there is soft power to be gained from such knowledge that could facilitate Singapore's role in shaping international environmental policies (e.g. United Nations Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction) and regional maritime security.

The sustainability of Singapore's coastline and its ability to fulfill the SDG 14 commitments and achieve its *City in Nature* goals depend critically on researchers' ability to deliver interdisciplinary scientific understanding and innovative applications beyond Singapore for a more sustainable sea space.

Despite the extensive research on Singapore's sea space as well as the regional work performed by researchers here, there has never been a strategic alignment of research direction and coordination of resources to build long-lasting academic and policy impact for marine environmental resilience. Based on the scientific outputs produced thus far in the nation, there is a clear trajectory for Singapore's research to create impact collaboratively across Southeast Asia and the broader tropical Asian region. However, researchers here have largely not stepped into regional and international leadership roles because of limited funding for research outside of Singapore. Most importantly, Singapore has grown capabilities over decades in several key areas, including biodiversity, ecology, microbiology and habitat restoration, but several other areas can be enhanced for meaningful integration and interdisciplinary research.

Therefore, this report tracks the growth of marine science in Singapore as a nation, and highlights gaps in knowledge on tropical urban environments as well as the capacity to carry out interdisciplinary marine science in this context. To seize the opportunities for sustainable growth in the oceans sector and safeguard marine assets for future generations, we present a new vision, map strategic research foci, and propose a national-level research programme. The research we are proposing focuses on Singapore's marine environment but in the regional context. Importantly, development and application of the best science to address current and emerging environmental challenges will advance Singapore's international standing in marine science.

KEY ENVIRONMENTAL CHALLENGES

Threats to the marine environment are not restricted to Singapore waters. Climate change affects marine habitats globally. Urbanisation is intensifying throughout the region, resulting in environmental threats similar to Singapore's as it was developing. Many of Singapore's coastal and marine ecosystems may already have exceeded their tipping points, due either to coastal urbanisation or climate change, or both. While species new to science and new species records for Singapore are constantly being uncovered—even at an increasing rate over the last few decades—most habitats have been declining monotonically over the same time period [8–11] (but see [12] for an exception). It is possible that species are being sustained by connected ecosystems and their populations in the surrounding region [13,14].

There is an urgent need to address these ecosystem losses through first understanding environmental dynamics and processes, followed by scientifically-informed habitat restoration and ultimately enhancing ecosystem resilience. More importantly, the key impacts on the region's marine environment need to be better understood and projected before targeted solutions can be developed and applied effectively.

Climate change

Climate change is profoundly impacting marine ecosystems through a variety of mechanisms. Rising atmospheric carbon dioxide levels and associated climate change effects are causing temperature rise, ocean acidification, deoxygenation as well as shifts in ocean circulation and nutrient levels, leading to extensive ecological impacts [15–17]. In fact, the previous time global carbon dioxide concentration reached modern levels of ~420 ppm is during the mid-Pliocene (~3 million years ago) when global temperatures were 2-3°C and sea levels more than 6 m higher than today [18]. For example, ocean acidification, a direct consequence of increased carbon dioxide, can interfere with their growth, reproduction, physiology and behaviour [19–24]. Across marine ecosystems, these changes result in decreased ecosystem productivity, altered food web dynamics, reduced abundance of habitat-forming species, shifting species distributions, and increased disease incidence [25–30]. The latter may even involve marine bacterial pathogens of humans driven by water temperature and nutrient availability acquired through seafood consumption or physical exposure to seawater [31,32].

Sea-level rise, driven predominantly in recent decades by thermosteric expansion and glacial melt [33], is also expected to cause seawater to inundate low-lying coastal areas and increase the water depth of shallow zones along the coastline. This effect can drown corals, seagrasses and mangroves not able to tolerate the reduced light in turbid marine environments typical of many areas in Southeast Asia [11,34–36]. Mangroves will be forced to retreat landward when sea-level rise and land-level subsidence exceed the threshold of 7mm/yr [37], exacerbating coastal erosion already observed in natural coasts of Singapore today which threaten coastal ecosystems.

The most visual manifestation of climate change in tropical marine ecosystems is coral bleaching, which results from expulsion of microalgal symbionts (Symbiodiniaceae) from shallow-water corals, en masse [38–40]. Several coral bleaching events have been documented in Singapore, including those syncing with the global-scale events of 1998, 2010 and 2016 [41–46], as well as a few local- or regional-scale bleaching [47]. While impacted species and reefs habitats do recover, full recovery of coral abundance has been shown to take up to half a decade on many of Singapore's reefs [48], and potentially even longer elsewhere [49,50]. Even if coral abundance increases back to pre-bleaching levels, longer-term ecological changes may have occurred, such as degradation of the impacted reef's structural complexity [51], loss of keystone species [48] and homogenisation of species persisting [52]. Crucially, changes can span biological scales below those of the corals and other macrofauna, including endosymbionts and microbial communities associated with coral host [53,54].

The impacts of climate change on marine ecosystems are complex, involving interactive abiotic changes and multifactorial biological responses. Ocean warming impacts could act synergistically with shifts in ocean chemistry to depress many organisms' performance and survival [55–58]. Altered ocean circulation affects larval transport, disrupting population dynamics already impacted by changes to seawater temperature and chemistry, leading to irreversible community-level changes [59,60]. Furthermore, synergies between climate change and other anthropogenic factors, such as coastal development and fishing pressure, are expected to exacerbate these effects further [61].

Biodiversity and habitat loss

The fast pace of coastal urbanisation, combined with extensive land reclamation projects expected to continue for the next decades, has led to the loss of habitats critical to Southeast Asia's rich biodiversity [8,62,63]. For example, studies have estimated losses of 70% of coral reefs, 91% of mangroves and 85% of sand/mudflats in Singapore since 1922 [64,65]. These declines are intimately linked to the loss of biodiversity, with only about 60% of historical records of coral species still being recorded in the past two decades [66–68]. These habitats are the foundation of the marine ecosystem; a decline in biodiversity and abundance can trigger cascading effects throughout the entire system, impacting everything from microbial communities to the larger marine life in our waters. These anthropogenic impacts have and will lead to a further decrease in the functional diversity of species, driven by the increasing dominance of stress-tolerant species in marine communities [43,45,48,69–71].

Alteration of coastal geomorphology due to land reclamation and coastal development also has far-reaching consequences for marine biodiversity (e.g., sediment bypassing along hardened coasts lead to smouldering of corals and seagrasses further downdrift). Due to the interconnectedness of the marine environment, changing hydrodynamic processes driven by geomorphological changes can lead to further unexpected impacts such as the erosion of population resilience and genetic diversity due to reduced connectivity [3,72,73]. These trends can result in further fragmentation of marine habitats which has been shown to decrease biodiversity and elevate the risk of local extirpations [74].

In the next decade, environmental solutions such as coastal protection measures which are intended to mitigate the effects of sea-level rise on low-lying areas would introduce new challenges for biodiversity and ecosystems [75]. While necessary for safeguarding infrastructure and human lives, these interventions can inadvertently harm habitats and disrupt local hydrology, creating a complex web of environmental impacts. Compounding these challenges is the threat of invasive species [76,77], particularly those introduced via ballast water and biofouling from various maritime activities [78–80]. Thus far, the few non-native species already established in Singapore have often outcompeted local flora and fauna, further destabilising ecosystems already under pressure from habitat loss and climate change [81,82].

In light of these multifaceted threats, it is crucial to recognise the urgent need for sustainable coastal development practices that would preserve Singapore's rich marine resources, even those beyond its borders. Indeed, there is a pressing need to understand and mitigate broader biodiversity impacts from activities such as mining of deep-ocean polymetallic nodules [83], to retain Singapore's capacity to reap long-term economic benefits. Failure to address biodiversity and habitat loss could therefore compromise not only its natural heritage but also the long-term viability of the nation's economy and quality of life.

Pollution

While regulations against trade effluent discharge are stringent, marine pollution remains a major concern for Singapore's marine environment [84]. One of the most immediate and visible impacts on the marine environment is caused by oil spills. For instance, the most recent oil spill that occurred on 14 June 2024 due to a marine collision off Pasir Panjang Terminal and the recent oil-leak at Bukom on 20 October 2024 highlight the potentially catastrophic consequences such events can have on marine life. Oil spills are a significant issue in Singapore due to the high volume of shipping traffic in our waters. Beyond the immediate ecological damage, oil spills also have long-term effects on marine ecosystems [85], but research on these impacts remains limited in Singapore and the region.

Another significant source of pollution is the input of sediments into the marine environment, caused by outfalls and various anthropogenic activities such as land reclamation, coastal construction and seafloor dredging. Sedimentation can physically abrade and smother benthic organisms, suffocating them under layers of deposited material [86–89]. The resuspension of these materials due to the hydrology and high traffic conditions of our waters can lead to increased water turbidity and reduce light penetration [90,91], hindering the growth of photosynthetic organisms such as seagrasses and corals [92–97]. Hard coral establishment on Singapore's coral reefs is generally restricted to depths shallower than 8 metres due to the extreme light attenuation, driving the dominance of low-light tolerant species in most coral communities [34,35,98]. There is a continual decline in cover and shift in the coral community and other fauna along the deeper reef slopes that are being replaced by unstable substrata such as rubble and silt [69,99,100].

Nutrient loading is becoming a greater concern recently because of an increase in aquaculture demand owing to Singapore's "30 by 30" food security goal. Excessive coastal input of nutrients, primarily nitrogen and phosphorus from excess feed and fish waste can lead to eutrophication which can trigger harmful algal blooms (HABs) on a frequent basis [101]. The anoxic conditions caused by HABs are not only a major concern for the functioning of marine ecosystems, but they can also have major human health and economic impacts [102,103] by driving the presence of bacterial human pathogens [104]. The marine HABs that occurred at least twice over the last decade are examples of how uncontrolled blooms can lead to significant economic losses for the aquaculture industry [105].

Other forms of pollutants that have been found in Singapore's marine environment include heavy metals, which have been detected in marine sediments and fauna [106,107], and have demonstrable impacts on various marine communities [108–110]. Plastic pollution, caused by the presence of particles ranging from nano-, micro- to macroplastics, is also evident here [111–113]. These pollutants can accumulate in the environment, leading to long-term damage to marine ecosystems [114–116]. Studies have shown that micro- and nanoplastics negatively affect organisms even at lower trophic levels, such as zooplankton and corals [117–119], with effects compounding through bioaccumulation and microbial activities, impacting species at higher trophic levels [120–122]. Not surprisingly, plastic pollution is also detrimental to human health [123]. As aquaculture becomes increasingly vital for food security, consuming fish reared in plastic-polluted environments poses serious health risks [124].

Circumstances in the broader Southeast Asian region can exacerbate local pollution. Singapore is situated in the confluence of multiple seas and reversing ocean currents are known to modulate its seasonal water quality [5,7]. Lack of proper wastewater management in some neighbouring areas, coupled with inadequate drainage infrastructure, result in untreated waste being discharged and potentially transported into Singapore's waters. Moreover, land-use change in nearby developing economies is expected to increase sediment load across the region, further intensifying sediment pollution. These cumulative impacts highlight the urgent need to develop regional legal frameworks and strategies for managing various pollution sources to safeguard Singapore's coastal health [125].

Food and energy

As Singapore strives to be more self-sustainable in terms of food and energy production, it is essential to consider the environmental impacts that accompany these efforts. While the nation's drive for self-sufficiency is commendable, particularly with initiatives like the "30 by 30" plan, there is a pressing need for more research and informed decision-making.

One of the key challenges in achieving these goals is the lack of comprehensive information on the local environmental influences and impacts of food production and aquaculture. As Singapore intensifies its aquaculture industry to meet the growing demand for locally produced food, the marine environment could face significant pressures. The expansion of aquaculture may lead to complications such as the spread of diseases among marine species [126,127], nutrient loading that can cause HABs [105], development of antimicrobial resistance due to the increased use of antibiotics [128], and the potential misuse of growth hormones [129]. The downstream effects not only harm marine ecosystems but also impact human health and the sustainability of food production in the long term. Indeed, the exit of Barramundi Group from farming in the Singapore Strait, due primarily to disease and high cost, is symptomatic of the complex dynamics facing sea-based farming in the waters here.

Similarly, the push for sustainable energy solutions, such as solar and tidal energy farms, though essential for reducing reliance on fossil fuels, brings about environmental uncertainties. While preliminary testing has assessed the short-term feasibility and impacts of these facilities [130], the long-term environmental consequences are largely unknown. Many green energy facilities are also using seawater for cooling their equipment and the discharges of warm water may be contaminated by polluting chemicals. The installation and operation of large-scale facilities on or adjacent to the sea could disrupt marine habitats, alter water currents, and have unforeseen consequences on local biodiversity.

Moreover, one of Singapore's strategies to strengthen food and energy security is "growing overseas"—expanding operations of local companies abroad in order to diversify reliable import sources. There is responsibility for Singapore to ensure overseas endeavours are also sustainable and not pollutive, especially given the interconnected nature of the regional seas around Singapore.

Given these complexities, it is crucial for Singapore to proceed with caution. Comprehensive environmental assessments, applied research to develop solutions, and strengthening of capabilities to deal with future environmental impacts of food and energy production are vital. These parallel activities will help ensure that the nation's pursuit of resource security does not come at the expense of its environmental health.

Complex sea space

Balancing the competing needs of various industries, food security, recreation and conservation is a complex challenge for Singapore’s limited sea space (see Box 1). The remaining natural ecosystems, while resilient in many ways, are still sensitive to contaminants and nutrient discharges, as evidenced by the impacts of HABs and declining ecosystem functioning [48,105]. Serious environmental degradation has been observed in many coastal areas, and climate change and coastal urbanisation will worsen conditions even faster [11,131]. Critically, the increasing demand is occurring while the sea space is projected to shrink even further because of emerging climate change mitigation needs such as coastal protection against sea-level rise, which can disrupt coastal environmental processes such as surface circulation and sediment transport [132,133].

While Singapore's agencies and ministries actively adopt a coordinated, whole-of-government approach to address specific environmental challenges, research supporting the sustainability of the marine space and blue economy remains fragmented. Better coordination of research across the marine science landscape can improve the policymaking process, leading to more efficient and optimal use of sea resources. Given the complexity of the marine environment and the diverse stakeholders involved, a broad spectrum of science-based strategies is essential to enhance environmental performance [134]. Specifically, establishing a unified marine research programme that addresses the full suite of challenges facing the marine environment of Singapore and the region would be a crucial step toward a more sustainable blue economy.

Box 1: Multiple complex uses of Singapore’s sea space

Singapore’s national plans with existing use or future activation of marine spaces:

- **“30 by 30”** – Strengthening food security by boosting local production. Expansion of sea-based farming activities in the Singapore Strait.
- **Singapore Aquaculture Plan** – National plan to transform Singapore's aquaculture sector for sustainable and productive urban tropical aquaculture.
- **Greater Southern Waterfront** – Transforming the area from Pasir Panjang to Marina East as a new major gateway and location for urban living along Singapore’s southern coast.
- **Long Island** – Coastal protection and reclamation works extending from Marina East to Tanah Merah, creating ~800 ha of new land.
- **Recreation Master Plan: An Island of Green, Blue and Fun** – Plans for further activating green and blue spaces, including the Southern Islands, for recreation to enhance quality of life.
- **City in Nature** – As part of the Singapore Green Plan 2030, with plans for 200 ha of new nature parks by 2030, including a second marine park in the Southern Islands and reef restoration (100,000 Corals Initiative).
- **Tuas Megaport** – Positioning Singapore as a global hub port and international maritime centre.
- **Energy Reset** – As part of the Singapore Green Plan 2030 to use cleaner energy sources across all sectors. Renewable energy plans include solar panels above the sea surface and harvesting marine tidal energy.
- **Other coastal development** – Other land reclamation works are being planned at various areas around Singapore including Woodlands Checkpoint, Changi Bay, Lorong Halus and the Southern Islands.

TRAJECTORY OF RESEARCH AND DEVELOPMENT

There have been nearly two centuries of research on the marine environment of Singapore, with the earliest descriptions of biodiversity performed as part of the first oceanographic expeditions, such as the United States Exploring Expedition, which collected and described new species from Singapore's coral reefs in the mid-1800s [135]. As biophysical, ecological and evolutionary theories were only starting to be developed in the 19th century through the mid-1900s, much of marine science research pre-independence were qualitative descriptions of Singapore's coastal environment, including faunal compilations [136,137] and physico-chemical measurements [138], which established simple baselines on biodiversity and environmental seasonality. While these baselines are outdated considering the rapidly changing coastlines and environment due to urbanisation and climate change following Singapore's independence, they remain valuable for understanding the trends of ecosystems and species today [48,67,139].

Post-independence, Singapore researchers capitalised on global and general advances in ecological patterns and processes to describe the particular environments of local ecosystems, including characterisation of ecological zonation in coral reefs [140,141] and mangrove forests [142,143]. Nearly all of these descriptive studies were published in grey literature and reports from regional meetings in the 1970s and 1980s (e.g. [144–147]). At the same time, quantitative studies were being published in international peer-reviewed journals (Figure 3). The extensive coastal urbanisation and utilisation in Singapore resulted in the need for better understanding of trends and environmental impacts [8,93,100,148,149], with studies emerging from many regional collaborative outfits, including the Regional Marine Biological Centre for Southeast Asia that was operational in the 1970s and the ASEAN-Australia Living Coastal Resources project that ran from 1986 to 1994 (see Box 2).

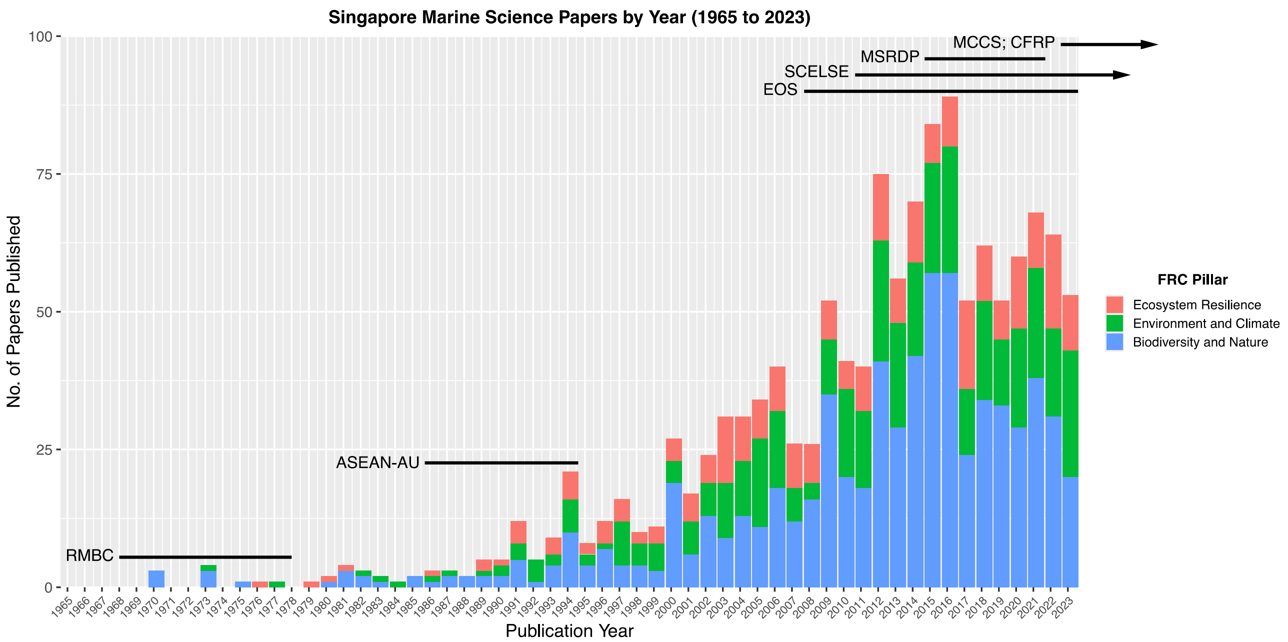

Figure 3. Volume of international peer-reviewed publications on the marine environment of Singapore since independence (1965). Major national-level marine science programmes are indicated for specific time periods (RMBC: Regional Marine Biological Centre for Southeast Asia; ASEAN-AU: ASEAN-Australia Living Coastal Resources; EOS: Earth Observatory of Singapore; SCELSE: Singapore Centre for Environmental Life Sciences Engineering; MSRDP: Marine Science R&D Programme; MCCS: Marine Climate Change Science; CFRP: Coastal Protection and Flood Management Research Programme). See Appendix 1 for methodology of compilation and categorisation, as well as the temporal distribution of publications within the four strategic domains of RIE2025.

Box 2: Singapore's role in marine science in Southeast Asia and beyond

Singapore has been involved in marine science research on the Southeast Asian region since its independence. The Singapore Government, along with UNESCO, established the Regional Marine Biological Centre for Southeast Asia at the then-University of Singapore in 1968 to manage the sorting and analyses of plankton samples collected from the Kuroshio Current and South China Sea by various countries (Figure B1). This Centre was active through the 1970s and led to many baseline studies of the biotic and abiotic environments of pelagic habitats (e.g. [150]) through to the 1990s [151]. Much of the material collected from these expeditions remain in the Lee Kong Chian Natural History Museum and is the basis for recent comparative studies on Singapore's plankton communities [152,153].

Singapore also took a co-coordination role in the ASEAN-Australia Living Coastal Resources project that ran from 1986 to 1994, funded and led by the Australian Agency for International Development and involving five ASEAN nations—Indonesia, Malaysia, Philippines, Singapore and Thailand. This programme initiated long-term, systematic quantitative monitoring of the major ecosystems of coral reefs, mangrove forests and seagrass meadows in each of the participating nations. Monitoring of mangrove forests and seagrass meadows did not continue into the new millennium, although it inspired several other programmes around the world, including the Global Mangrove Watch [154] and Seagrass Watch [155], utilising a wide variety of monitoring methods. Importantly, the ASEAN-Australia project seeded sustained support for reef coral monitoring, gradually transforming into the Southeast Asia node of the Global Coral Reef Monitoring Network (GCRMN), which has been responsible for producing periodic status reports of its coral reefs [46,156–160]. Today, both the Northeast and Southeast Asian nodes of the GCRMN are coordinated by Japanese researchers, and the outcomes have had significant impacts on long-term ecological monitoring and conservation in East Asia [45,161,162].

Support for regional marine science research continues to this day, but are often subsumed within general research grants, institution-specific programmes or philanthropic funding and not through national-level marine science programmes. For example, units in IHLs such as the Lee Kong Chian Natural History Museum (LKCNHM) and Department of Biological Sciences (DBS) at NUS run programmes to bring regional scientists to Singapore to work on specific projects (e.g. LKCNHM's 20-year-old SPRINT programme). There are also several researchers and thought leaders serving as experts in international initiatives such as the Ballast Water Management Convention, Clarion-Clipperton Zone environmental management plan, and the United Nations Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction. Numerous regional expeditions have also been organised by IHLs, including the 2018 South Java Deep-Sea (SJADES) Biodiversity Expedition organised by LKCNHM and then-Lembaga Ilmu Pengetahuan Indonesia (LIPI).

The Marine Science R&D Programme (MSRDP; see *Marine Science Research and Development Programme* below) also set aside seed funds for preliminary research on environments outside of Singapore. Through the limited funding, researchers embarked on studies that benefit from regional and even global sampling, investigating the evolutionary histories of various taxonomic groups [163–168], microbial and endosymbiont diversity of host-associated species [169–177], and biogeochemical links between Singapore's coastal waters and the surrounding seas [6,178,179].

Singapore has the potential to take a more prominent role in ASEAN marine science, but this will require a concerted and strategic broadening of its research foci. A national marine programme that creates initiatives centred on Singapore but also spearheads regional collaborations—ensuring that research is aligned with both national and regional priorities—would achieve this milestone.

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SINGAPORE GOVERNMENT PRESS STATEMENT

Regional Marine Biological Centre for Southeast Asia

The Ministry of Education (on behalf of the Government of Singapore) recently concluded an agreement with UNESCO to establish and develop a Regional Marine Biological Centre in Southeast Asia, at the University of Singapore.

Under the Agreement, UNESCO will make available specialised equipment such as microscopes, valued at US$6,000/-; and the University of Singapore will make available equipment to the value of at least US$7,000/-; in addition to a fully-furnished research laboratory. UNESCO will also make an annual financial contribution amounting to US$16,000/- during 1968. The University of Singapore's matching contribution of US$16,000/- will be by way of the supporting administrative, research and technical staff as well as the annually recurrent expenditure for the maintenance of the Centre.

Initially the Centre will be used for sorting the many thousands of samples of plankton, the food of many species of fish, which are collected by the research vessels of many nations actively participating in the co-operative study of the Kuroshio Current and South China Sea. These countries include Japan, Russia, U.S.A, Taiwan, the United Kingdom, Indonesia, the Philippines, Vietnam and Thailand. The work of this Centre will contribute towards a better understanding of the biology of many species of economic food fishes in this region, thereby leading to a more rational approach to the exploitation of these marine resources by all interested countries. The role of this Centre will be complementary to those of the Fishing Training Centre and the Fisheries Development Research Centre being established by the Singapore Government at Changi.

The Regional Marine Biological Centre has been established under the directorship of Dr. Tham Ah Kow and is located in the Science Faculty, University of Singapore, Bukit Timah.

The Deputy Prime Minister, Dr. Toh Chin Chye, will officially declare open the Centre on Tuesday, 19th March 1968 at 5.15 p.m. The opening ceremony will be held in the New Lecture Theatre Four of the University of Singapore, Bukit Timah. Among the guests invited to witness the opening of the Centre are participants, observers and UNESCO officials who will be in Singapore attending the UNESCO 4th Regional Meeting of Marine Science Experts in East and Southeast Asia. Following the opening ceremony there will be a small demonstration of the work undertaken by the Centre, and a reception, for the guests.

15TH MARCH, 1968. TIME ISSUED: 1245 HOURS.

Figure B1. In 1968, the Singapore Government and UNESCO established the Regional Marine Biological Centre for Southeast Asia in Singapore.

The volume of international peer-reviewed publications has increased over time since the 1970s and 1980s, which saw less than a handful of papers published per year, till today, with publications exceeding 50 per year over the last decade (Figure 3). When the papers are categorised into three broad subjects reflecting the key pillars of marine science that research performers have engaged in—(1) Biodiversity & Nature, (2) Environment & Climate, and (3) Ecosystem Resilience—the growth can be separated into three main phases.

During the 1990s, there was a proportionate rise in publication rate for each of the three pillars, driven by a strong foundation for research in Biodiversity & Nature. The 2000s saw an increase in output primarily fuelled by work on Environment & Climate, as well as Ecosystem Resilience, following the establishment of the Tropical Marine Science Institute (TMSI) in 1996 and its marine lab at St John's Island in 2002. The output on Environment & Climate continued its growth during the third phase in the 2010s with publications from the Research Centres of Excellence, the Earth Observatory of Singapore (EOS) established in 2008 and Singapore Centre for Environmental Life Sciences Engineering (SCELSE) set up in 2011. The Comprehensive Marine Biodiversity Survey conducted between 2010 and 2015 was wholly supported by private philanthropic funds and contributed over 60 publications in 2015 and 2016 on Biodiversity & Nature, with approximately 1300 species (including about 100 new species) identified from 70,000 specimens [180,181].

Based on these developments, the need to study and enhance Ecosystem Resilience, the third key marine science pillar, was addressed by the Marine Science R&D Programme (MSRDP) during 2015–2021. This programme contributed to the later growth of publications associated with Ecosystem Resilience, particularly on strategies for restoring degraded habitats [43,53,182–185]. Clearly, nationally-coordinated marine science programmes that strive to integrate research directions across institutions can help level up emerging research themes, especially those harnessing greater application potential.

In the following, major research programmes and infrastructure that have contributed to the growth of marine science in Singapore over the last two decades are described.

Research Centres of Excellence

Two Research Centres of Excellence (RCE) have been established within the last two decades to address environmental challenges in Singapore and its surrounding region, with varying levels of focus on the marine environment. The first, the Earth Observatory of Singapore (EOS), was established in 2008 to perform fundamental science research on geological and coastal geohazards as well as climate change in and around Southeast Asia. While EOS originally included a marine science component, it was not fully developed in the establishment of the centre. Marine-related projects EOS undertakes in collaboration with the Asian School of the Environment (NTU) are typically related to geological scales in space and time. For example, research includes understanding how physical reef structures and their ecologies (species, assemblages and ecosystems) provide coastal resilience in Southeast Asia. Palaeoenvironmental studies on how our ancient coastline responded to past sea-level rise also shed light on possible mangrove responses to future sea-level rise [186].

The second RCE with marine-related research is the Singapore Centre for Environmental Life Sciences Engineering (SCELSE). SCELSE is an interdisciplinary team of microbiologists focused on biofilm communities. Their marine research focuses on scaling microbes from the gene, molecular and cellular level to ecosystem-wide processes and finding solutions in microbial engineering. Such engineering problems include pathogen detection in aquaculture, biofilms that digest plastics and manipulating their role in biofouling and corrosion. An area of expanding focus is on holobiont systems (a host organism and its associated biofilm or microbiome, e.g. corals and seagrasses) which are studied in detail to assign roles in imparting ecosystem resilience and microbially mediated responses to climate change. By comprehensively addressing the microbial component of marine systems, SCELSE is building a holistic understanding of Singapore's marine and coastal ecosystems, from identifying structure-function relationships that drive the ecology of these systems to developing numerous applications and translational advances.

Ministry of Education (MOE) Academic Research Fund (AcRF)

Numerous Tier 1 and Tier 2 grants have been awarded on projects with a marine focus. Over the past decade, the vast majority of such projects have been in the engineering domain, but a handful are focused on marine science, specifically under the Environment & Climate pillar:

- *Validating the Pacific Centennial Oscillation: Integrating models and paleo-data* (PI: Adam Switzer, NTU; Jan 2017 to Jan 2020)
- *Monitoring sea-level change in SE Asia with the innovative use of GPS* (PI: Emma Hill, NTU; Jun 2017 to May 2020)
- *Relative sea-level changes along the Northern Sea Route: from patterns and rates to drivers and mechanisms* (PI: Benjamin Horton, NTU; May 2021 to Apr 2024)
- *Decomposition and environmental impacts of terrestrial organic carbon in the South China Sea* (PI: Patrick Martin; Feb 2022 to Feb 2025)
- *Characterising the role of the sea surface micro layer in regulating microbial dispersal, human exposure, and pollutant transformation* (PI: Federico Lauro, NTU; Jan 2023 to Jan 2027)
- *Tracking sea surface temperature change in the tropical Indian Ocean over the past five centuries* (PI: Wang Xianfeng, NTU; Feb 2023 to Jan 2026)

Two of the projects relate to palaeoclimatological reconstructions of the environment, including sea surface temperature, precipitation and salinity. Sea levels in Southeast Asia and the Arctic are the foci of two of the projects, together with a MOE-AcRF Tier 3 project, the Southeast Asia SEA-Level Program (SEA2), led by Benjamin Horton (NTU) from Sep 2020 to Sep 2025. The remaining two projects contain a significant life sciences component—one on the flux of dissolved organic carbon from land to the ocean, to measure and model biogeochemistry of coastal and oceanic waters for SE Asian region; and another characterising the sea surface microlayer and its biotic and abiotic components for understanding air-sea exchanges. All these projects are particularly important for climate modelling, for which there is a lack of information in this region. The funding and resources needed to study coastal and marine systems beyond Singapore's shores are relatively scarce, especially in the context of national-level marine science programmes, but which has been the hallmark of MOE AcRF projects.

National Research Foundation (NRF) Academic Research

Funding Initiatives that come under NRF's Academic Research Horizontal include the Competitive Research Programme (CRP), NRF Fellowship and NRF Investigatorship. Three marine science-related CRP projects have been funded in the last decade. Two of these projects are focused on aquaculture and aligned with the Biodiversity & Nature pillar, while the third focuses on the effects of microbial biofilms on the corrosion process and is aligned with the Environment & Climate pillar.

AQMARINOME2016: Increasing Singapore's food fish production through aquaculture genomics R&D, led by Laszlo Orban (Temasek Life Sciences Laboratory) from Feb 2012 to Jan 2017, aimed to apply genomic resources in Asian seabass to accelerate genetic gains and deliver climate-resilient food fish for profitable and sustainable aquaculture in Singapore. The whole genome sequencing (and re-sequencing) improved population structure resolution of the Asian seabass, facilitating analysis of genetic diversity. The data and findings have contributed to the development of genomics-based assays that enhance the productivity and quality of important food fish species in Singapore. Further, the molecular tools developed are being adapted to the aquaculture systems of other tropical marine fish species, advancing their production systems from traditional into modern, science-assisted aquaculture. These enhancements have helped accelerate marine aquaculture research directed by the Singapore Food Agency (SFA) and carried out by companies such as Barramundi Group and Singapore Aquaculture Technologies.

Development of virus-controlling biotechnologies for cost-efficient and sustainable aquaculture was led by Ge Ruowen (NUS) from Feb 2012 to Feb 2018, was predicated on the need for new biotechnologies to combat viral diseases in cost-efficient and sustainable aquaculture systems. It developed an early-warning system for fish aquaculture systems, and hence sustainable practices. Specifically, it unveiled structure-function relationships for targeted drug design and, and thus identified host factors, antiviral molecules and interactions for subsequent employment in infection biology and pharmaceutical intervention of viral diseases in aquaculture.

Unlocking the secrets of microbially influenced corrosion: From detection to control mechanisms, led by Federico Lauro (NTU) from Jan 2020 to Dec 2024, investigated the metabolic activity of microbial biofilms on metal structures and the associated corrosion process. In the marine environment, more than 20% of the entire cost of corrosion damage can be attributed to microbially influenced corrosion. This project advanced laboratory and field techniques for microbially influenced corrosion research, including the development of a novel high-pressure chemostat with simultaneous real-time monitoring of corrosion rates, accurately simulating deep-sea conditions. Different sulphate-reducing bacteria were identified to either increase or protect metals against corrosion and, when corrosive, displayed different types of pitting corrosion. Overall, a range of predictive management solutions, including strategies utilising bacteria, can be developed for Singapore's maritime industry.

The Singapore NRF Fellowship is awarded to early-career researchers for a five-year research programme, aimed at attracting top young scientists to come to Singapore to develop independent research here. Five Fellows focusing on marine science-related topics have been funded, nearly all working on topics closely aligned with the Environment & Climate pillar:

- Adam Switzer (NTU): *Geological records of coastal hazards in southeast Asia* (May 2010 to May 2015)
- Emma Hill (NTU): *Towards a better understanding of climate change and natural hazards in and around Southeast Asia through geodetic data combination* (Jun 2011 to Jun 2016)
- Natalie Goodkin (NTU): *The Oceanographic Perspective: Reconstructing seasonal climate variations in the Indo-Pacific using coral geochemical records* (May 2012 to Apr 2017)
- Aron Meltzner (NTU): *Sea-level and land-level change in Southeast Asia: A geological approach to quantifying hazard from rising seas and earthquakes* (Jun 2019 to May 2024)

Only the most recent project, Kyle Morgan's (NTU) "*Back to the future: Integrating multiscale coral reef functions in Southeast Asia*" (Apr 2022 to Mar 2027) has ventured into the Ecosystem Resilience pillar. The Biodiversity & Nature pillar is not represented by the NRF Fellowship. One of the NRF Fellows, Emma Hill (NTU) was also awarded an NRF Investigatorship as a leader in the field of research to perform ground-breaking, high-risk research for the project '*Space-borne geodesy and remote sensing for understanding natural hazards, sea-level change and disaster response in Asia*' (Apr 2019 to Mar 2024), also within the Environment & Climate pillar.

Singapore agency-directed research

Various funding initiatives established by agencies have been instrumental in enabling research driven by Singapore's research performers yet addressing national-level planning and operational needs. For example, the Technical Committee on Coastal and Marine Environment (TCCME) established in 2007 and co-chaired by the National Parks Board (NParks) and National Environment Agency (NEA) is an inter-agency coordination mechanism that brings together stakeholders of Singapore's coastal and marine environment. Through research projects initiated and funded by TCCME, the Committee aims to address issues pertaining to the multi-sectoral utilisation of Singapore's coastal and marine space.

As most of the agencies are concerned with the monitoring and conservation of Singapore's coastal and marine ecosystems while enabling multi-sectoral utilisation of the sea space, most of the projects focus on a single ecosystem or environmental issue but are cross-cutting in generating solutions across the three pillars of marine science—Biodiversity & Nature, Environment & Climate, and Ecosystem Resilience. The following is a list of supported projects that are related to marine science and oceanography:

- *Development of a multi-organism and multi-level biomarker system for biomonitoring of marine ecosystem health* (NParks/TCCME; Mar 2016 to Sep 2019)
- *Development of an adaptive framework for assessing risk to environmental stress: an energetics approach to safeguarding Singapore's corals* (NParks/TCCME; May 2018 to Aug 2020)
- *Environmental DNA detection of the invasive mussel* Mytella strigata *in Singapore* (NParks/TCCME; Oct 2018 to Jul 2020)
- *Marine debris in Singapore: Establishing a national baseline, citizen science monitoring and data sharing* (NParks/TCCME; Mar 2016 to Jan 2021)
- *Marine invertebrate-associated bacteria: Microbial diversity & applications toward conservation efforts* (NParks/TCCME; Oct 2018 to Apr 2021)
- *Field trial on the use of clay for harmful algae bloom control* (SFA; May 2020 to Mar 2022)
- *Underwater acoustic monitoring of marine megafauna within Singapore's noisy coastal waters* (NParks/TCCME; Apr 2019 to Jan 2023)
- *Monitoring and prediction of harmful algal blooms (HAB)* (SFA; Mar 2020 to Mar 2023)
- *Eco-cement for protection of coastline and enhancement of marine ecosystem* (MND/NParks; Apr 2021 to Mar 2023)
- *Assessing the efficacy of Singapore's largest artificial reef structures for biodiversity conservation, research test-bedding, and promoting marine environment outreach and education* (NParks/TCCME; Feb 2021 to Jan 2024)
- *Connectivity of fish populations in marine areas of Singapore* (NParks/TCCME; Oct 2021 to Dec 2024)

For example, the project "*Assessing the efficacy of Singapore's largest artificial reef structures for biodiversity conservation, research test-bedding, and promoting marine environment outreach and education*" involved monitoring and enhancing the biodiversity on artificial reefs. It also provided empirical derivation of physiological and biochemical trait data (e.g. coral calcification rates, bleaching susceptibility) that will be critical in shaping reef restoration and management work in Singapore. Specifically, the project quantified coral recruitment and epibiotic colonisation on the surfaces of artificial reef structures in the context of abiotic factors such as depth or surface orientation. It also spearheaded educational activities such as raising public awareness of marine science and Singapore's marine conservation efforts, and training volunteers for assisting with coral monitoring, maintenance and data collection.

The MND/NParks eco-cement project was an interdisciplinary study involving geoengineering, marine biology and electro-chemistry. It developed novel eco-friendly materials to enhance marine ecosystems associated with coastal protection infrastructure, thus contributing to Singapore's innovation and manufacturing capabilities in the marine science sector.

Marine Science Research and Development Programme

The Marine Science R&D Programme (MSRDP) (2015–2021) initiated a coordinated inter-IHL marine science programme that unified the best ideas and talents across Singapore's research ecosystem to address diverse issues in our marine environment (see Box 3). A total of S$25 million from NRF supported 33 projects (including seed projects) over two grant calls.

Four research themes were established to focus the proposals toward addressing specific knowledge gaps on Singapore's coastal and marine ecosystems, mitigating ongoing environmental threats, and developing solutions to specific problems. The themes were (1) Marine Ecosystems and Biodiversity, to understand and protect marine ecosystems; (2) Environmental Impact and Monitoring, to identify and mitigate potential environmental stresses and hazards; (3) Coastal Ecological Engineering, to develop solutions for enhancing coastal development and sustainable marine environment; and (4) Marine Technology Platforms, to integrate marine science with applications in engineering design, antifouling, etc. The programme operationalised top-of-the-line equipment such as the particle image velocimetry system to measure physical properties of seawater, and various systems to comprehensively characterise seawater chemistry (e.g. analysers and sensors for nutrients and carbonate chemistry, semi-preparative HPLC).

NRF National Research Infrastructure (NRI)

Marine science infrastructure has also been enhanced alongside the MSRDP, including the NRF-funded controlled environment aquaria at the St John's Island National Marine Laboratory (SJIMML; S$18.4 million, 2016–2021; S$19.3 million, 2021–2026; see Box 3) and the smart, extensible buoys of the Marine Environment Sensing Network (MESN; S$9.2 million, 2020–2025).

Prior to its NRI designation in 2016, the marine station on St John's Island had been running as a TMSI facility since October 2002. Today, with strong and sustained support by various partner entities, including IHLs, polytechnics, national research centres such as A*STAR, EOS, SCELSE and TLL, governmental agencies and industry, SJINML is a shared national facility open to all marine science researchers (local and international). The main goals of SJINML are to: (1) enhance the quality of national marine science R&D; (2) conduct research of strategic significance relevant to national agencies; (3) catalyse collaborations that enhance strategic national and international research programmes; (4) increase high-impact research outputs in sustainability research; and (5) implement manpower training programmes to support future needs in marine science.

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 10-m 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. SJINML also maintains the only research vessel (i.e., RV Galaxea) capable of offshore field sampling and data collection.

Operating out of SJINML, the MESN is a multi-institution effort to better assess ocean health and address key issues facing Singapore's waters. Key partners include TMSI, NTU, Singapore University of Technology and Design (SUTD) and Agency for Science, Technology and Research (A*STAR), together providing expertise in marine engineering, marine ecology and biogeochemistry, and data technology. MESN aims to increase the collective pool of knowledge and understanding of Singapore's marine environment by establishing three buoys equipped with a variety of research-grade sensors, collecting data on over 30 environmental parameters in real-time. The buoys also serve as a platform for the test-bedding of novel marine technologies. The widening availability of MESN data encourages the collection of biogeochemical and biological data localised to the MESN buoy positions. Ongoing support for the MESN is critical for integration of the environmental data collected into global models. This ultimately helps identify environmental feedback to biomes essential for predictive models with the capabilities to enhance Singapore's marine ecosystem resilience.

Box 3: National-level marine science programmes and infrastructure

Marine science research has only been coordinated at the national level immediately following Singapore's independence, when the Ministry of Education established the Regional Marine Biological Centre for Southeast Asia in 1968, and in more recent years. Without inter-IHL integration in the intervening years, research capacity and reputation was built primarily in specific fields such as in Biodiversity & Nature (see *Potential for excellence* below). Between 2015 and 2021, the National Research Foundation (NRF) supported the S$25-million Marine Science R&D Programme (MSRDP) (2015–2021) to coordinate research across IHLs on diverse issues related to Singapore's marine environment. A total of 33 projects, including two large anchor projects (>S$5 million each) and several seed projects, were carried out (Figure B2).

Within just six years, the MSRDP led mostly by NUS and NTU researchers produced over 200 high-quality publications. It built up local capacity by developing a strong talent pool of 119 Singapore-based RSEs and training 35 PhD, 16 MSc and 51 polytechnic students. These talents worked with researchers from nearly 20 institutions overseas, completed 26 collaborative projects with national agencies and companies, and over 75% of all the researchers involved in the programme are now embedded in local and international scientific industries. In fact, 85% of research scientists and PhD graduates remain in science-based employment, with Singapore retaining well over 70% of these scientists. The outsized results produced by the MSRDP clearly point to the need for such nationally coordinated programmes if Singapore's marine science capabilities—across academic, industrial and governmental sectors—were to be strengthened further for addressing marine environmental issues locally and globally.

Figure B2. MSRDP Director, Professor Peter Ng (right), with PIs and agency stakeholders at the concluding MSRDP Conference in 2021.

At the same time that the MSRDP was initiated, the marine lab at St John's Island established by TMSI (NUS) was transformed by NRF to serve researchers and educators across Singapore as a National Research Infrastructure, with funding tranches of S$18.4 million for 2016–2021, and S$19.3 million for 2021–2026 (Figure B3). The St John's Island National Marine Laboratory (SJINML) hosts various field and aquarium facilities for Singapore's researchers (Figure B4). Backed by a team of trained and skilled manpower and a network of stakeholders in research, industries, and agencies, SJINML has become a physical focal point for marine science research in Singapore.

Figure B3. St John's Island National Marine Laboratory (SJINML), an NRF-funded National Research Infrastructure.

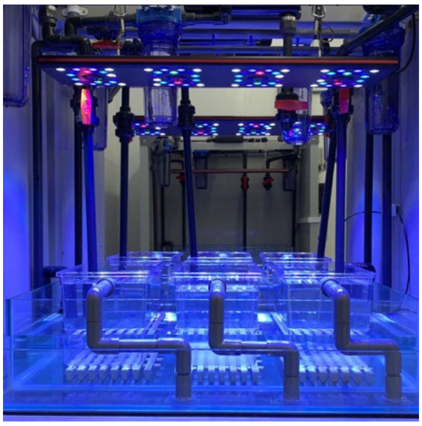

Figure B4. Climate-controlled aquarium at SJINML.

Over the past eight years, SJINML has galvanised researchers from IHLs and polytechnics in Singapore to form a dynamic multidisciplinary community of marine scientists. The community along with partner institutions have provided infrastructure supporting the research of over 350 local and overseas academics and students from more than 25 institutions and organisations since 2016, including projects under all four RIE2025 domains. During the recent oil spill incident in June 2024, SJINML played a key role in coordinating and providing scientific support for initial environmental surveys around St John's Island, and will continue to support MND's Integrated Oil Spill Response and Habitat Recovery Plan.

SJINML has a strong student community, which has also been beneficial in attracting the next generation to take up marine science–related jobs and careers. SJINML's education and outreach programmes have contributed to increased public awareness of the marine science and conservation work in Singapore. These include partnerships with the National Parks Board for the Marine Parks Outreach and Education Centre and the 100,000 Corals Initiative, as well as working closely with MOE Curriculum Planning and Development Division to develop capabilities and resources for marine environment education that are aligned with the Singapore school curriculum.

NRF International Relations

In the last decade, bilateral collaborative research programmes focused on marine science have been initiated between Singapore and the UK, Australia and Israel. Projects initiated between the Natural Environment Research Council (NERC) and NRF that ran between 2020 and 2023 introduced marine plastic research to Singapore's R&D portfolio. Prior to this, smaller, less comprehensive projects on marine plastics were undertaken in an ad-hoc manner. The programme *Understanding plastic pollution impact on marine ecosystems in Southeast Asia* injected £3 million from NERC to support the UK research community and low-to-middle-income countries in Southeast Asia, alongside another S$5 million from NRF to support researchers from Singapore. The projects supported were:

- *Sources, impacts and solutions for plastics in South East Asia coastal environments*
- *Microbial transformation of plastics in SE Asian seas: A hazard and a solution*
- *South East Asia MArine Plastics (SEAmap): Solutions and integrated strategies for the reduction, control and mitigation of marine plastic pollution in the Philippines*
- *Risks and Solutions: Marine Plastics in Southeast Asia (RaSP-SEA)*

In addition to marine plastic research performed with the UK, other international collaborative programmes include studies of contemporary and paleo-ecological coral communities co-funded by Israel Science Foundation (ISF) and NRF from 2018 to 2021:

- *Reproductive strategies of fungiid corals along wide-ranging latitudes: The coral reefs of Eilat (Red Sea) vs. Singapore (South China Sea)*
- *Using molecular and paleoecological methods to discover temporal and spatial ecological variations between two coral reef systems in the Indo-Pacific*

NRF Urban Sustainability Solutions

The most recent marine research funding initiated under NRF's Urban Sustainability Solutions strategic domain of the RIE2025 has been organised through the Marine Climate Change Science (MCCS) programme implemented by NParks, as well as by NRF's White Space funding.

The ongoing MCCS programme is supported by S$25 million of funding and serves as a national hub for interdisciplinary marine climate change research to address the challenges faced by our coastal and marine environment arising from climate change. By focusing on multidisciplinary and translational research, the MCCS programme strives to advance the foundational sciences of marine climate change and support the creation of evidence-based interventions and solutions. These efforts are aimed at protecting our coastal and marine ecosystems from climate change impacts, such as rising sea levels, increasing sea surface temperatures, and extreme storm events. Research efforts are integrated through three core research verticals (Blue Carbon Science, Eco-Engineering and Ecological Resilience) and two enabling horizontals (Marine Climate Impact and Community-Driven Climate Resilience Planning). The projects that have been awarded so far are:

- *Assessing the carbon storage and sequestration potential of blue carbon resources in Singapore*
- *Enhancing the ecological resilience of coral reefs in response to climate change stressors*
- *Investigation of wave attenuation over mangroves and seagrass*
- *Assessing the long-term viability of nature-based climate solutions to future sea level rise and marine heatwaves in Singapore*

These research directions have been identified through dialogue and consultation with domain experts, statutory boards and government agencies. Of note, three key areas were identified during discussions in 2019 and 2020 among PIs of the MSRDP for research continuity via a second phase of the MSRDP: (1) Eco-resilience in an urban tropical marine environment; (2) Eco-engineered shorelines for greater urban liveability; and (3) Blue carbon: Conservation and restoration of tropical coastal ecosystems as natural climate solutions. The latter area and topics associated with climate change impacts and solutions formed the basis of the MCCS. However, the remaining areas identified for continuity of the MSRDP have remained unsupported at the national level.

White Space funding aimed at developing strategic capabilities and regional collaborations in marine science include *The Second Joint Singapore-Indonesia Deep-Sea Biodiversity Expedition* (Sep 2022 to Aug 2025). Most recently, to address the climate-driven challenges of coastal and inland flooding in Singapore stemming from sea-level rise and more frequent extreme storms, the Coastal Protection and Flood Management Research Programme (CFRP) is being implemented by the Public Utilities Board (PUB) with S$125 million funding under RIE2025. This new programme has been established as part of a multi-institutional Centre of Excellence hosted at NUS, with partner institutes NTU, Singapore Institute of Technology (SIT), SUTD and A*STAR.

The CFRP consists of four research verticals to build new capabilities and technologies for enhancing Singapore's coastal and flood resilience: (1) Innovative Engineering Solutions for Coastal Protection and Flood Management, (2) Integrated Nature-based Solutions for Coastal Protection, (3) Sustainable Infrastructure Solutions for Coastal Protection and Flood Management, and (4) Smart Management Solutions for Coastal Protection and Flood Management. These are supported by three cross-cutting horizontals of advancing coastal science research to deepen understanding of extremities and changes in coastal processes affected by climate change; enhancing capabilities in monitoring, prediction, and digitalisation of Singapore's coastal environment; and developing an effective framework to support integrated and adaptive planning, to strengthen risk management and decision-making processes when prioritising investments made in coastal and flood protection infrastructure.

Now is an opportune time to continue investing in marine science R&D, capitalising on the competencies and operational infrastructure to integrate research across the marine science landscape. This would augment and empower ongoing initiatives such as the MCCS programme and CFRP that focus especially on climate-related risks. Specifically, a national research programme for marine science that cuts across disciplines to address current and emerging environmental issues is needed. This will enable Singapore to continue raising the capabilities and profiles of our research performers globally. Crucially, we are well-positioned to develop the research capacity to export sustainable and responsible innovation to neighbouring tropical Asian economies on whom we remain dependent for many resources. Indeed, Singapore should seize the economic opportunities arising from a collective ability to address future marine environmental challenges.

ENHANCING RESEARCH AND COORDINATION

A cutting-edge, inter-IHL programme that integrates across Singapore's research ecosystem and builds on knowledge and ideas generated by the MSRDP, MCCS and CFRP is needed to address the wide range of marine environmental issues in Southeast Asia and the broader tropical Asia. There remain opportunities for the existing ecosystem to raise the impact and sustainability of such a research programme. This requires stakeholders to embed a long-term strategy that reimagines the current parameters defining our capabilities and research direction.

Research continuity and strategic planning

Continuity of marine science research is often challenged by shifts in the funding landscape. Changes in the availability or focus of funding require adaptations in the direction and nature of the work. Such shifts are pronounced in marine science, where funding is often acquired on an ad-hoc basis. The MSRDP unified the Singapore's research ecosystem and coordinated across IHLs, polytechnics and research institutes for broad and impactful marine science research. However, only few components of the programme have been continued in the ongoing MCCS programme and CFRP.

The framework for interdisciplinary research established by the MSRDP and SJINML, supported by academic, governmental and industry partners, needs to be sustained for further progress. A new marine science programme is urgently needed to build upon these foundations before they disintegrate once again. Singapore's marine scientists are dispersed across various institutions, few of which have the critical mass required to compete globally. Collectively, however, we possess critical mass as well as a world-class research infrastructure and environment. What is missing is a robust research framework that fosters sustained collaboration across these institutions.

To address these challenges, it is crucial to enhance communication and collaboration between IHLs and other research entities, funding agencies and stakeholders. Instead of engaging in disruptive competition, institutions and researchers should adopt cooperative approaches, share resources, and align their goals. This helps sustain research momentum, even during periods of fluctuating funding. Such collaboration not only enhances the stability of ongoing projects but also ensures that valuable research continues to progress, contributing to a more resilient and innovative scientific community.

Integrated environmental information and solutions

Singapore is home to one of the most extensively studied marine systems globally [187]. The country has a long history of data collection across biological, chemical, and physical oceanographic fields, often employing cutting-edge methods of their time. However, significant data gaps persist, primarily due to limited temporal coverage caused by funding interruptions. The most critical challenges are the dynamic nature of Singapore's coastal waters—driven by rapid urbanisation—and the region's high biodiversity [84,188–190]. Additionally, certain localities, such as the MINDEF live-firing areas, have been inaccessible to researchers for nearly four decades [191]. These challenges are further exacerbated by insufficient funding for region-wide research (see *Opportunities for regional approaches* below), limiting our understanding and impeding precise environmental modelling of Singapore's marine systems, which play a crucial role in various assemblage networks, population connections, biogeochemical cycles, and oceanographic processes [3,5,169–171,173–177,192,193].

Critically, marine stakeholders including agencies have underscored the current lack of environmental data relevant to their operational needs, such as environmental impact assessments, and the necessity for an integrated environmental model. Such a model would help capture the marine environmental carrying capacity and provide insights into Singapore's overall marine health trends. Addressing the fragmented nature of our marine science data landscape is critical for Singapore to enhance its blue economy while preserving the biodiversity needed to maintain a healthy and vibrant marine environment.

Opportunities for regional approaches

Marine ecosystems are interconnected beyond national boundaries, making it essential for marine research to extend beyond Singapore to encompass the broader region. Currently, there is a significant lack of regional coordination of data collection and sharing, which hampers our ability to understand and manage these interconnected ecosystems effectively. A key challenge is funding. Most funding streams are restricted jurisdictionally, making it difficult to share resources with international collaborators. There is a pressing need for regional funding initiatives specifically aimed at building research infrastructure and capacity in other tropical Asian countries. This would not only enhance the region's ability to conduct comprehensive marine research but also foster stronger scientific partnerships.

There is room to enhance multilateral Southeast Asian cooperation in marine science. A coordinated regional research network is essential to facilitate collaboration, share data, and synchronise research efforts. Such a network would improve the efficiency and impact of marine research across the region, leading to better management and conservation outcomes. Indeed, Singapore needs to take on a more prominent role in the region to help coordinate marine science research efforts. This involves creating initiatives that are centred on Singapore but have a regional focus, ensuring that research is aligned with both national and regional priorities. These initiatives should not be limited to piecemeal research projects around the region; instead, they should be strategic and designed to address key regional issues.

More broadly, a critical gap exists in the representation of ASEAN countries at international environmental science platforms, including the Conference of the Parties under the United Nations Framework Convention on Climate Change and the Convention on Biological Diversity. Singapore is well-positioned to contribute to ASEAN's representation in these forums. This will ensure that the interests and needs of the region are adequately represented on the global stage, fostering a more unified and influential voice on marine conservation for ASEAN.

Enhancing collaborative research

Apart from the uncertainty of the current funding landscape driven by changes in the availability and focus of funding, the scale of existing funding does not align with the ambitious goals of collaborative research programmes. The MSRDP featured substantial anchor projects designed to tackle challenging research questions, alongside smaller capacity-building projects aimed at enhancing core capabilities. This model supports interdisciplinary research by involving multiple institutions and co-PIs, thereby fostering synergies that produce outcomes greater than the sum of their parts.

In marine science projects, however, research efforts have often been limited to a small number of lead researchers. While the MSRDP allocated approximately S$5 million per anchor project—averaging around S$1 million per co-PI—more recent projects under the MCCS programme are funded by only half that amount on average. This reduced funding is inadequate for generating the desired synergistic outcomes. For example, each co-PI may not have sufficient resources to hire postdoctoral researchers, which are crucial for driving cross-cutting research and collaboration within the team. To support effective collaborative research, larger grant sizes are essential. Nevertheless, smaller competitive grants remain critical for research performers to respond quickly to emerging research fields, especially these opportunities they are available at more frequent intervals.

Generating targeted solutions

A key feature of the coastal and marine environment is the diverse range of stakeholders with varying interests. Therefore, it is crucial to translate research findings into practical management strategies and on-the-ground implementation that involve as many of the stakeholders as possible. We advocate for a shift of the knowledge creation process from a co-design to a co-production model, which encourages researchers and stakeholders to work together in co-producing scientific knowledge [194]. This collaborative approach, with strong stakeholder engagement, can help secure ongoing funding and significantly boost the overall impact of research.

Building cross-institutional and cross-agency cooperation requires establishing trust between agencies and research institutions, with effective knowledge and data exchange being crucial to this effort. Ideally, research data should be used to develop solutions for coastal and marine management practices, such as conservation prioritisation and marine spatial planning [134,191,195].

Identifying gaps in capacity to develop specific solutions reveals several challenges within the marine science research community. For example, there is a shortage of design engineers collaborating with biologists to develop more efficient experimental setups. Similarly, we lack researchers skilled in fluid mechanics, which is crucial for understanding marine processes. Additionally, expanding the pool of bioinformatics experts is necessary to manage, process and interpret the growing volume of genomic data. However, poor career prospects are leading to a decline in foundational knowledge of organism biology and physiology, a trend that must be reversed to sustain progress in the field.

Infrastructure for sustainable talent development

To ensure marine science research is sustainable in Singapore, the ecosystem must continue to be strengthened specifically for retaining talent. This involves prioritising the development, recognition, and retention of research talent, particularly early-career scientists. The MSRDP had an excellent record in this respect, with the vast majority of all the researchers involved in the programme continuing to contribute to local and international scientific industries. This programme thus serves as a strong model for training and retaining marine science experts, demonstrating how strategic initiatives can help build a robust and sustainable research community.

There is however a limit as to how long these early-career researchers will remain in the academic system. A sustainable research programme would create more opportunities for research positions such as senior and principal research fellows at institutions such as TMSI. Additionally, it is crucial to establish roles that are not dependent on specific research leaders and performers, ensuring that the work continues seamlessly even as PIs come and go. That outstanding researchers (e.g. NRF Fellows) have chosen to start their careers in Singapore shows that the ecosystem can attract the best talents, but their retention will be an important step to sustaining high-quality, impactful outcomes.

COMPETITIVE ADVANTAGE AND POTENTIAL FOR EXCELLENCE

Despite the challenges outlined above, which are largely surmountable, the marine science research ecosystem currently has a solid foundation and a critical mass of talent and infrastructure to drive further advancements. Supported by a robust academic environment and favorable biogeographic conditions, it should strive for global excellence in areas where it has already established significant strengths, while also investing in other key areas to enhance its capacity for interdisciplinary research.

Strong global academic standing

NUS and NTU are recognised as top universities globally, with NUS ranking 8th and NTU 15th in the QS World University Rankings 2025 (19th and 32nd respectively in the Times Higher Education World University Rankings 2024). This prestigious standing helps attract top talent to initiate research programmes, which can be strategically directed to benefit the research ecosystem further, whether through interdisciplinary research or by strengthening both new and existing areas of expertise. Additionally, high-quality PhD graduates are drawn to work on projects as postdoctoral researchers, enhancing the research capabilities of these institutions and ensuring positive outcomes. The strong reputation of IHLs also facilitates international collaborations (see *NRF International Relations* above) to expand upon the topics Singapore’s research performers would typically engage in and to further enhance the capacity for interdisciplinary research.

Sustained governmental commitment

Singapore's funding landscape for research and innovation remains promising in the next decade, and this trend is likely to continue if the current investment by the Singapore Government of 1% of Singapore’s GDP for RIE2025 is sustained. While funding directions may shift depending on changing priorities, the country remains an attractive destination for international academics due to the research opportunities available.

Currently, there are numerous small grant opportunities, with a significant number of MOE AcRF Tier 1 and Tier 2 grants being awarded for marine science projects. In contrast, MOE AcRF Tier 3 and CRP grants are less common in this field. Many researchers may prefer smaller grants, which allow them to focus on narrowly defined but critical problems, typically within the realm of applied research. These grants also help to build core capabilities that are essential for future collaborative research efforts. However, smaller grants may limit the scope for interdisciplinary research. Large-scale collaborative research projects require substantial funding, as evidenced by the successful outcomes of the MSRDP anchor projects.

Beyond funding, several government agencies have been instrumental in supporting Singapore's marine science research ecosystem. A national-level platform which was recently proposed for a NRF Mid-Size Grant and a MOE AcRF Tier 3 project received backing from NParks, Maritime and Port Authority, NEA, PUB and SFA. These agencies recognise the importance of science in informing policy decisions and implementing adaptive management solutions to optimise the use of Singapore's limited sea space. For instance, Singapore's “30 by 30” goal to enhance food security is increasingly grounded in scientific strategies to expand marine aquaculture while maintaining environmental quality and protecting sensitive ecosystems. The Government is also taking the lead in initiatives to enhance ecosystem resilience, such as the 100,000 Corals Initiative, a national effort to restore degraded coral habitats and create new ones, including on coastal protection structures. These efforts are aligned with Singapore's aspirations to achieving its *City in Nature* goals as part of the Singapore Green Plan 2030 [2]. Such initiatives signal Singapore’s commitment to global environmental sustainability and strengthen its role in shaping international policies, particularly in the areas of urban coastal management and conservation [4].

Excellent research infrastructure and human capital

Robust governmental support over the past decade, particularly through the MSRDP and NRI platforms, has significantly enhanced shared facilities and resources and boosted the research talent pool. All IHLs and polytechnics involved in marine science research, including NUS, NTU, SIT, SUTD, Republic Polytechnic, Singapore Polytechnic and Temasek Polytechnic, as we well as various national research centres, governmental agencies and industrial partners, have contributed significantly to building the marine science ecosystem.

On the NRI, however, it is important to note that the lease at St John's Island to operate the SJINML currently extends only until 2029, which may pose challenges for long-term planning and stability. Nevertheless, Singapore is known for its socioeconomic stability and strategic foresight, with detailed plans laid out for the use of both land and sea space (e.g. Urban Redevelopment Authority's Master Plan for the next 10–15 years, and the Long-Term Plan over the next 50 years and beyond). This commitment to long-term planning, coupled with economic and social stability, supports sustained research efforts and fosters an environment where researchers can thrive.

Overall, Singapore boasts strong human capital, characterised by highly trained personnel who are quick to launch into new research areas and adopt new technologies. A culture of open collaboration and long-term relationships has fostered a close-knit community, which is welcoming to new members. There is a strong willingness among researchers to share resources, further enhancing the collaborative environment. Despite this openness, Singapore's manpower hiring policies and bureaucracies may hinder the involvement of foreign researchers, potentially resulting in the loss of highly qualified staff and collaborators.

Fortunately, decades of marine science research with involvement from the public sector have resulted in a high level of trust and respect afforded to researchers. This respect contrasts with experiences in some other countries, where researchers may face greater obstacles accessing coastal and marine areas for research. In Singapore, the process of obtaining permits and other necessary paperwork is streamlined and centralised, with NParks acting as an intermediary with other relevant agencies. This practice minimises barriers to entry and facilitates the smooth conduct of research (except for MINDEF live-firing areas).

Beyond Singapore's shores, our research performers have established a strong regional network in specific marine science topics to facilitate research. For example, Singapore's membership in the Global Coral Reef Monitoring Network (GCRMN) has enabled its researchers to carry out a study of the long-term trends of coral reefs in the East Asian region [45,46,162]. SJINML has also begun establishing a working network of marine research stations in Southeast Asia that is expected to play a crucial role in connecting researchers and promoting a collaborative approach to understanding regional marine environments [196,197]. In a region that is often data-sparse, there is a critical need for such regional networks to pool resources for marine monitoring and fostering scientific understanding of our shared sea space and ocean processes.

Biogeographic advantages

Singapore is located near the world's center of marine biodiversity, just west of the Coral Triangle biodiversity hotspot [198]. This region's rich diversity of various floral and faunal groups—including corals, seagrasses, mangroves, and fish [199–203]—provides an invaluable resource for scientific research. Few places globally offer the unique combination of distinct tropical ecosystems—coral reefs, seagrass meadows, mangrove forests, and mudflats—within such a compact area as Singapore's marine space [11,65]. Research has shown that the periphery of biodiversity hotspots like this one generate complex ecological and evolutionary processes [204–207]. For example, biogeographic models indicate that coral diversity often emerges in these peripheral zones [208–211], highlighting their conservation value in terms of both functional and evolutionary importance [212,213]. Furthermore, complex oceanographic processes drive the genetic connectivity of Singapore's key marine species with other marine ecosystems in the surrounding region [13,193,214], making this an exceptionally interesting location for scientific study. Singapore is also located at the centre of the tectonically stable Sunda Shelf, with elevations suitable for sea-level and climate research with accommodation space to preserve sediment archives of past sea-level and coastal change [131,215]. Such research is critical for elucidating the complex relationships between sea level, ice sheets and climate. Such research has international significance given the paucity of such data in our region relative to the higher latitudes.

As a highly urbanised nation situated along the equatorial belt in Southeast Asia, novel and diverse assemblages of species also thrive on artificial habitats, such as those on seawalls and other artificial structures [216–220]. This combination of high biodiversity and urbanisation creates a unique setting for research [36,221]. Additionally, the logistics of conducting research in equatorial regions like Singapore can be more cost-effective compared to higher latitudes, where specialised equipment like drysuits and cold-water dive gear may be required.

Singapore's experience with its degrading marine environment may foreshadow the future of other developing economies in Southeast Asia. Instead of aiming to restore ecosystems to a pristine state—an unattainable goal—research here has focused on how we can coexist more sustainably with nature [222–224]. The sustained emphasis on the *City in Nature* goals reflects this approach [2], driving the integration of biodiversity into urban spaces and reducing the impact of local impacts on the broader marine systems in the region. Singapore can thus serve as a model for other emerging megacities throughout Southeast Asia, demonstrating how harmonious relationships between urban development and nature can be co-created by various stakeholders [225,226].

Potential for excellence

Singapore has a relatively small research ecosystem focusing on marine science. A total of 45 PI-level researchers could be identified to have been working on marine science research here over the past few years. This is comparable to the number of researchers based at a typical mid- to large-sized oceanographic institution in North America, Europe and Australia, e.g. University of California Santa Barbara Marine Science Institute, Plymouth Marine Laboratory and Australian Institute of Marine Science. Nevertheless, Singapore's research performers have clearly done well in terms of the volume of work produced.

Based on bibliometric data from Scopus analysed with SciVal (https://www.elsevier.com/products/scival), we computed the Field-Weighted Citation Impact (FWCI) metric for all research performers publishing in marine science topics and obtained the 20 institutions with the highest aggregate FWCI (Figure 4). The average number of publications produced by each of these top institutions from 2014 to 2023 is 1069. Singapore's research performers published a total of 1008 papers over the same period. This is more than large institutions such as Plymouth Marine Laboratory (n=715) and University of California Santa Barbara Marine Science Institute (n=908), and reflects the high productivity of marine scientists here despite the small research ecosystem in Singapore.

The aggregate FWCI of 1.30 among Singapore's research performers is significantly lower than the range of FWCI (1.90–2.12) for the top 20 institutions (Figure 4), meaning that marine science papers published by Singapore researchers garner 60–80% fewer citations than those by researchers in the top 20 for publications in similar fields. This is striking because Singapore performs as well as many top 20 institutions in Biodiversity & Nature research, but is falling behind in topics related to Environment & Climate as well as Ecosystem Resilience. In fact, its FWCI of 1.65 for Biodiversity & Nature is higher than that of the 4th, 7th and 8th-overall best performing institutions—University of Tasmania, University of British Columbia and CSIRO, respectively. Singapore's FWCI for Environment & Climate of 1.15 is lower than the range of 1.52–2.64 for the top 20 institutions; its FWCI for Ecosystem Resilience of 1.15 falls within the lower part of the range of 0.84–3.54 for the top 20 institutions. Such differences between the three pillars are not unique to Singapore, but are evident in just three top 20 institutions (Figure 4).

To drive the development of effective strategies for managing Singapore's complex sea space and supporting a sustainable blue economy, all three marine science pillars need to advance in tandem. More research to enhance our understanding of Singapore's environment and climate trajectories is needed so that their impacts on biodiversity—for which there is strong foundational knowledge on species and habitats—can be curtailed through solutions targeted at raising ecosystem resilience [227,228]. However, smaller-scale studies tend to draw lower impact in terms of applications and citations [229,230], so broadening the scope of marine environmental research to regional and global scales, whenever there is scientific rationale to do so, would generate greater academic impact.

Overall, Singapore needs a research programme that plugs the larger knowledge gaps in Environment & Climate and invests in Ecosystem Resilience through applied research, while maintaining Singapore's strength in Biodiversity & Nature that has been built over several decades. The marine science ecosystem continues to mature owing to the critical mass of research performers achieved through recent national-level programmes and Singapore's competitive edge for research. Consequently, a unified research direction, leveraging existing and new strengths in marine science, will help grow Singapore's research profile for advancing the interests of stakeholders of tropical Asian seas sustainably.

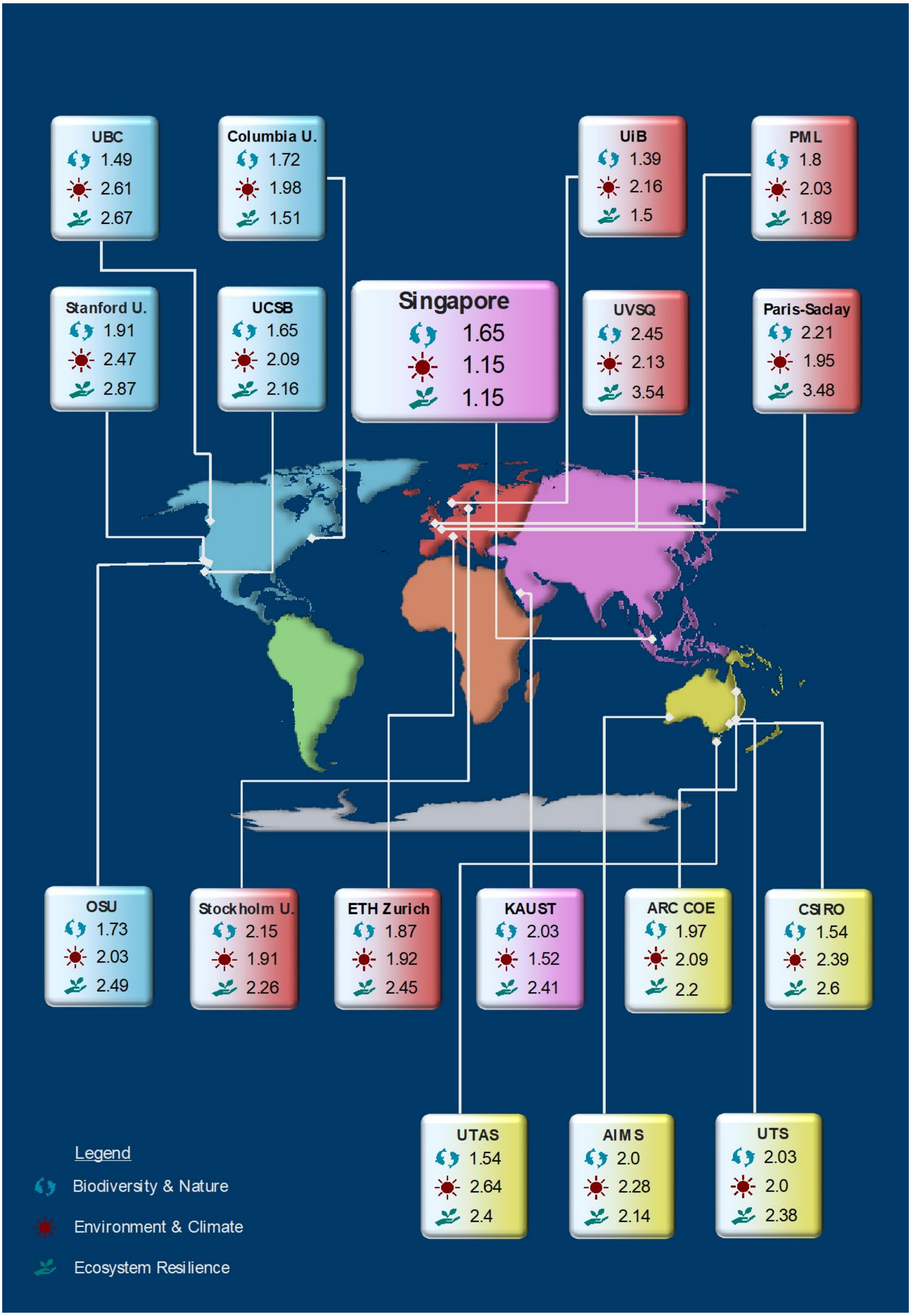

Figure 4. Top 20 institutions with the highest aggregate Field-Weighted Citation Impact (FWCI) for marine science publications globally. FWCI values indicated for each institutions are specific for each of the three pillars of marine science. Singapore's associated research performance is separately shown.

RESEARCH PRIORITIES AND STRATEGY

To address the environmental challenges before us, leveraging the strengths of Singapore marine science research ecosystem, and the opportunities arising in the field regionally and globally, we propose a National Initiative for Marine and Ocean Sciences (NIMOS). We envision this new research programme to bring together Singapore's research talents, infrastructure and resources, as well as decades of foundational research to deliver *whole-of-coast* (i.e. systems-level) solutions for sustaining Singapore's blue economy. Owing to the increasing number of stakeholders and utilisation of Singapore sea space, our ability to manage and direct its resources to benefit the nation hinges on new scientific tools which our ecosystem has the capabilities to deliver. Failure to understand the marine environment adequately can compromise our ability to extract economic value from the sea space. For example, the exit of Barramundi Group from the Singapore's aquaculture space due to fish disease and other ecological and economic reasons may have been avoided with targeted environmental studies prior to the Group's most recent expansion.

A sustainable blue economy should therefore balance marine utilisation with ecosystem preservation by enhancing environmental resilience [231,232]. Achieving this requires interdisciplinary research and innovation in areas such as circular systems, ecosystem services and integrated ocean management [233]. Successful development and implementation of blue economy policies requires research that considers the needs of all stakeholders while sustaining the resilience of marine ecosystems against current and future threats [234,235]. A key research priority in this regard pertains to the translation of scientific data and knowledge into policy and environmental management, and more broadly social science approaches that will align research outputs with policymaking. The intrinsic value of marine ecosystems can also be raised by strategic outreach and education efforts to boost the nation's ocean literacy.

Above all, research excellence through strategic collaboration must be a priority of the new programme. It should enable discovery of fundamental understanding but at the same time incentivise the application of discoveries to develop targeted solutions, such as rapid and cost-effective technologies for biodiversity monitoring and environment sensing. Research projects should incorporate space and resources to explore beyond operational goals directed by national agencies, so as to address perennial blind spots and better inform policy. It should also continue to build environmental baselines and push the bounds and continuity of long-term data, which are most critical for training AI and other modern tools to make meaningful projections. Spatial upscaling of these datasets and analyses to the broader region around Singapore will only increase the precision and value of the projections. Finally, it should leverage the work and outcomes of recent programmes such as the MSRDP and MCCS. From the perspective of climate adaptation and mitigation, the equatorial and urban setting of Singapore's ecosystems would facilitate our understanding of the synergistic impacts of local and climate pressures. It also offers a unique opportunity to create nature-based solutions that would be relevant to many tropical Asian environments.

NIMOS would be hosted at IHL(s) in close partnership with government agencies and national research infrastructures such as St John's Island National Marine Laboratory (SJINML). The IHL(s) would serve as NIMOS' secretariat and house a core team of Singapore-based world-class marine scientists pursuing the abovementioned research priorities. NIMOS would adopt a hub-and-spoke model, whereby existing and future national and international research institutes, programmes and initiatives could plug in to NIMOS as key partners and stakeholders (Figure 1).

NIMOS can serve as a "research aggregator", bringing together not just the marine scientists in Singapore, but also from around the Southeast Asian region. Long term challenges in the health of our regional seas are vital to Singapore's economy and long-term sustainability. NIMOS can also serve as a research "pit stop" in tropical Southeast Asia for international scientists, and as a hub for marine science research and training for the region. Efforts are also underway to engage our regional marine laboratories to form a network of labs for facilitating movement and exchange of researchers in the region. Currently, no such network exist in Southeast Asia or under the ASEAN framework. NIMOS will create the enabling conditions to strengthen our local and regional linkages, engender greater opportunities for international research collaboration, and translate research to actions for the benefit of coastal and marine ecosystems and communities in Singapore and beyond.

Research by NIMOS will be delivered through three integrative marine science pillars—(1) Biodiversity & Nature, to establish baselines and fundamental knowledge of the functioning of marine ecosystems; (2) Environment & Climate, to determine environmental limits and characterise key ocean processes vital for safeguarding ocean and human health under climate change; and (3) Ecosystem Resilience, to develop adaptation strategies to retain, rejuvenate and restore key ecosystem functions and services. These parallel and interdependent research themes leverage the strengths of Singapore's researchers and the competitive advantage of our research ecosystem (including established research infrastructure and resources) to build new understanding and foundations beneficial for Singapore.

The scientific verticals will be underpinned by three key horizontals to extend the reach of the new knowledge and applications to the wider community of stakeholders: (1) Marine Technologies, for the design and broad implementation of innovative and technology-driven solutions; (2) Marine Policy, Governance & Law, to produce a science-based framework to support environmental management and decision-making associated with the utilisation of Singapore's sea space; and (3) Ocean Literacy, to improve the public's engagement and understanding of marine science so critical for an island nation surrounded by a myriad of sea-based risks and opportunities. Overall, the programme's vision is to maximise the biodiversity, functioning and resilience of Singapore's urban coastal environment for supporting a vibrant and sustainable blue economy.

Biodiversity & Nature

Globally, marine ecosystems provide goods and services totaling about US$50 trillion every year, which is larger than the combined GDP of the 10 largest economies in the world, based on estimates in 2011 [236]. The distribution of these ecosystem values is spatially heterogeneous, and the quality of the services is highly dependent on levels of biodiversity and habitat quality [237]. Despite the diversity of life being one of the most fundamental issues in science, and even with over two and a half centuries of work discovering and describing species globally, the vast majority of marine biodiversity remains unknown. This is a serious impediment for marine science as biodiversity data, estimates and information are critical for marine conservation and management. For example, spatial patterns of species richness are often an important criterion for the prioritisation of marine areas for nature conservation and protection, but no precise estimates for the number of species in any marine habitat exist anywhere on Earth.

Tabulating known species has become more manageable in the Information Age, but estimating total species diversity remains challenging because the rate of species discovery has not declined. Some taxa such as marine mammals, mangroves and seagrasses are extremely well characterised, but the majority of marine groups may have more species unknown than known, with between one-third and 90% of all existing species remaining to be discovered [238–240]. Even among very well-studied organisms such as sharks and rays, our research shows that only 16 of 47 detected through sequencing DNA present in seawater are known to science [241]. Another recent study deployed a limited number of standardised collecting devices (Autonomous Reef Monitoring Structures, or ARMS) designed to recruit organisms that tend to hide within the complex structural framework of coral reefs (otherwise known as the cryptobiome), demonstrating that less than one-third of species across all major groups of marine organisms could be identified to species [242]. For severely understudied groups such as worms (Annelida), as few as 2.5% of all detected species could be recognised with an existing species name. More taxonomists and technological advances are accelerating the discovery process, but by and large, predictions based on current sampling rates have not converged. Species are also being lost faster than they are being discovered [243,244].

Singapore's location in the tropical Southeast Asia mega-archipelago, which contains the richest marine biodiversity on Earth, provides strategic opportunities by being a gateway to extraordinary resources in the South China Sea [18] and Coral Triangle [19], from which a sustainable blue economy may be derived. With a small sea space of just over 1,000 km^2, and continually decreasing due to land reclamation, this is one of few coastal nations where it is possible to fully characterise the nation's marine biodiversity and genetic resources. Few projects around the world have aspired to build a comprehensive biodiversity inventory, including the Moorea Biocode Project [245,246] and SANTO 2006 [247], focusing on South Pacific islands. These projects have not achieved this valuable scientific milestone, although they have expedited species discovery and enhanced diversity estimation.

A complete inventory of species within a nation's jurisdiction is important not just for establishing a reliable environmental baseline and for addressing longstanding ecological questions, it will also help realise Singapore's blue economy potential [248]. The data could even be vital for defending a country against cross-border environmental degradation or allegations [249,250]. Indeed, Singapore was brought to the International Tribunal for the Law of the Sea in 2003 by Malaysia to halt the island nation's reclamation works around Pulau Tekong and Pulau Ubin, alleging that the activities are causing transboundary environmental damage to Malaysia's territorial waters. Without sound biodiversity data, Singapore could compromise its ability to reclaim land for national needs.

Through this Biodiversity & Nature pillar, NIMOS will estimate the complete biodiversity of Singapore's marine environment. This will require building ecological models to understanding the distribution of species and for targeting specific areas for detailed collections. For most tropical marine habitats, organisms falling with the size ranges between the microscopic single cells (e.g. Bacteria, Archaea and Fungi) and the macrofauna—generally the eukaryotic micro- and meiofauna—are considered the "black box" of biodiversity [251,252]. Anthropogenic activities such as aquaculture and coastal development invariably increase the level of sediment in the water column that eventually settles onto the seafloor [95,253], which hosts a wide range of organisms, especially the poorly studied micro- and meiofauna. Characterising and quantifying these species across benthic habitats will fill a critical biodiversity gap in Singapore and the tropics generally. Findings are expected to reveal not only the mechanisms by which sediment impacts environmental health, but also how sediment-associated biota contribute to coastal biodiversity.

The biodiversity inventory will enable the construction of robust community models that incorporate species' physiological and reproductive traits, as well as interactions via food webs, symbioses and competition of intra- and interspecific forms. The functions of each species within the community can be quantified for resilience enhancement and targeted restoration efforts [254–256]. The models can also help forecast the trajectories following environmental disturbances, such as the recovery of coastal habitats after oil spills, as well as identify pioneer communities and how they change over time. More broadly, this approach empowers various fields to find and select new model organisms for research (e.g. genotypic and phenotypic studies) and for industry applications. For example, ex situ breeding and culture of organisms to help supply or replace species in the vast aquarium trade in the region can be predicted with such comprehensive ecological models.

Biodiversity resource monitoring and management can be enhanced by leveraging the species inventories and community models to identify indicator organisms to forewarn ecosystem changes [252,257–260]. This approach requires community and population trends to determine key indicators for environmental degradation or improvement [261]. To this end, data for marine species have been consolidate in a few major biodiversity research programmes, including the Comprehensive Marine Biodiversity Survey (2010–2015) and most recently the third edition of the *Singapore Red Data Book: Red Lists of Singapore Biodiversity*—a product of the partnership between NParks, NUS's LKCNHM and Nature Society Singapore that lists over 3,000 marine species in Singapore [139]. This effort needs to be extended to the poorly studied micro- and meiofauna for a more complete picture of tropical marine biodiversity.

Finally, a deeper understanding of the spatiotemporal distribution and reproductive ecology of species will aid in managing human-wildlife conflicts. For example, sightings of dangerous marine animals like the venomous box jellyfish are increasing along Singapore's coasts. These animals can deliver painful, sometimes fatal stings, and have led to beach closures worldwide, including at Sentosa Island, Singapore. Developing a predictive model would allow management authorities to concentrate monitoring efforts on specific locations and times, improving coastal safety by restricting access where necessary.

Environment & Climate

Clean coastal waters and healthy marine ecosystems are critical for sustaining and optimising the many, often conflicting, activities by diverse stakeholders within Singapore's limited urban sea space. Appropriate environmental quality objectives (EQOs) integrated within mitigation and management strategies that are science-based and site-relevant are vital. However, environmental quality is a complex concept—it is neither absolute nor static, and is multidimensional. For dynamic tropical coastal and marine systems such as Singapore's, where large and erratic natural fluctuations dominate, assessing environmental quality and identifying potential threats to ecosystem health can be especially challenging.

Specifically, while discharges and effluents in Singapore are regulated and closely monitored with strict limits (i.e. by PUB and NEA), the complex factors that determine the extent of their impacts remain poorly understood (e.g. interactions of pollutants with suspended particles, biogeochemical transformations, and physical transport). The transport and fates of pollutants can be further complicated by climate change which is expected to further alter seawater chemistry and circulation [55,57,58]. Furthermore, while Singapore adopts the EQOs set by the ASEAN Marine Water Quality Guidelines (AMWQG), baseline levels of specific parameters at certain locations and time points (e.g. nutrients) have already exceeded the common marine water quality criteria set by this regional guideline [84,262].

Critically, there exist significant uncertainties in climate change predictions and climate effects on coastal systems in this complex region. Compounding these variabilities are consequences of human activities that can interact with climate change impacts to further deteriorate water quality [263]. In-depth understanding of the biogeochemical processes in such complex systems are therefore needed to accurately determine environmental states, establish context-relevant ecological triggers and thresholds, forecast ecosystem responses, and eventually enhance environmental resilience [264,265].

The Environment & Climate pillar will focus on research that informs strategies for ecological risk management and ecosystem protection, supporting sustainable development of Singapore's marine assets in the face of rapid environmental and climatic changes. One key area of research involves identifying locally-relevant environmental triggers and thresholds [134]. These thresholds are crucial for improving the accuracy and effectiveness of environmental impact assessments, guiding better management practices, and shaping more informed environmental policies [266]. Another area of focus is investigating and characterising marine pathogenic risks, particularly those that threaten both ocean and human health [267]. With the rise of global shipping, tourism and climate change, the risks of pathogenic outbreaks in marine environments have increased, necessitating research to detect, monitor, and mitigate these threats effectively [268].

Innovation is urgently needed in the development of advanced early-warning systems and integrated ecological models [269]. These tools are essential for proactive management of Singapore's marine resources, allowing stakeholders to anticipate and mitigate environmental risks before they escalate. The implementation of such technologies is aligned with the goal of developing a sustainable blue economy [270]. More generally, solutions are needed to maintain and enhance environmental quality in tropical urban settings. As urbanisation continues to accelerate, the balance between development and environmental preservation becomes increasingly delicate. Research in this area should explore sustainable urban design and pollution control strategies tailored to the unique challenges posed by tropical climates.

Apart from technological advancements, there is an urgent need to identify ecological risks and pinpoint resilient hotspots across the broader tropical Asia [271,272]. By doing so, stakeholders can jointly support the long-term sustainability of connected regional seas and the communities that depend on them. Understanding where these hotspots are located and what contributes to their resilience are critical for extending these safeguards on marine biodiversity to regional economies that rely on the resources. Together, these research directions are expected to help Singapore protect and sustainably manage its marine resources while providing insights that could be applied to similar ecosystems across tropical Asia.

Ecosystem Resilience

Singapore is uniquely situated as a highly developed nation on an equatorial island within Southeast Asia. However, this does not evoke a true picture of Singapore, which unexpectedly has extraordinary diversity within its coastal environment (e.g. [66,242,273,274]). Despite its recent, thoughtful development and innate ecosystem resilience, we face the challenge of protecting this tropical coastal environment as Singapore continues to urbanise.

Singapore's size and being an island subjects it to specific ecological paradigms. Importantly, the high diversity is a product of its equatorial location, species endemism and habitat for migratory species such as turtles and structurally complex flora and fauna such as mangroves and corals. However, islands are particularly susceptible to habitat loss and fragmentation due to their defined size [275,276]. Thoughtful design around known connectivity between populations is essential to their survival. Studies must also consider existing and emerging bottlenecks for populations and their microbiomes. Design of new habitat during land reclamation and coastal development, repurposing of an environment and construction of seawalls all offer opportunities for ecological engineering marine communities that enhance the ecosystem services and resilience of our marine environment (e.g. [277–280]).

Ecosystem engineering principles applied on seawall designs, apart from protecting the coastline from increasing storm action and rising sea levels, can encourage settlement of diverse habitat-forming species and increase coastal biodiversity [278,281–283]. New ecosystems created in these artificial settings, via the settlement of mangroves, seagrasses, seaweeds and corals, may also have positive spillover effects on the biodiversity of adjacent natural habitats. Together, new and existing functional ecosystems would provide increased goods and services, thereby optimising their biodiversity utility while considering their value in the stabilisation of the coastline.

This Ecosystem Resilience pillar will focus on the restoration of marine habitats and optimisation of artificial habitats to raise marine environmental resilience in Singapore's waters and beyond. An environmental framework that integrates natural, restored and artificial habitats, as well as their interconnectivity, is expected to better protect biodiversity, functioning and resilience for sustaining a productive blue economy. Research is needed to develop approaches that span community to cellular levels for solutions that have rigorous ecological and biological bases. Work is currently underway to identify methods for transplanting seagrasses and mangroves, and to establish corals. Critically important is identifying resilient genotypes, maintaining genetic diversity within populations and connectivity between populations [3,284]. Further work is also underway to characterise a wide range of microbiomes and identify specific microbial species that convey resilience [54,285–288]. Microbes have the potential to produce bioactive molecules that alter their hosts health, function, and resilience. They also perform biogeochemical transformations that condition the habitat to be favorable to its host and a succession species recruited to the habitat. The production of such bioactives has been a source of novel compounds with potential food, energy, medical and industrial applications [289–291].

Climate change effects are driving habitat-forming species and associated communities towards the tipping point between ecosystem functioning and collapse [15,292,293]. This is of critical important because crossing such tipping points will transform ecosystems, destabilise interconnected habitats, and disrupt ecosystem services [294–296]. Modelling our approach based on validated thresholds of marine ecosystems would allow the trajectories of habitats to be understood and projected more precisely. Such research is often reliant on measurements of growth and other physiological parameters of habitat-forming organisms such as corals and seagrasses. However, growth may not be correlated with health of species [297,298]. Indeed, growth is a distinct stage to homeostasis and death. The latter does have characteristic molecular markers at the cellular and genetic levels and would seem to be better proxies for modelling than a distinct life stage.

Programmed cell death (PCD) pathways are diverse but what they have in common is the precipitous decline in health when organisms cross specific tipping points [299]. Many well-studied model organisms have affirmed the link between PCD and caspase, a protease implicated in precipitous cellular damage leading to death [300,301]. Notably, PCD pathways and caspases have recently been identified in corals and algae [302–304]. Caspases have also been tracked through the tipping point of phytoplankton blooms, suggesting that this enzyme would be a better proxy for imminent death and growth [305]. Indeed, additional research is needed to understand cell death at the cellular level so that caspase expression through the various PCD pathways can be understood for interpretation of gene expression studies. Caspases are also excellent targets for extending a species resilience as they have the potential to arrest tipping points in which they drive the cellular damage leading to death [306–308]. Such ambitions as using the genes and proteins that underpin cellular processes leading to collapse of ecosystems will put Singapore at the cutting edge of predictive modelling for climatic impacts on marine ecosystems.

Finally, tropical coastal habitats (e.g. coral reefs, seagrass meadows and mangrove forests) do not exist as ecosystems in isolation. The biophysical, ecological and genetic connectivity between ecosystems generates complex spatial and temporal feedback loops that can affect water quality, biogeochemistry, population structure and ecosystem functioning, amongst others. Key features of this feedback remain poorly understood. Therefore, it is of critical importance that large collaborative studies be undertaken so that specialist research in each ecosystem or contiguous component (such as biogeochemistry or population genetics) can be undertaken and interpreted between them. The multipronged approach proposed here would be much more likely than single factorial studies to accurately predict the pleotropic and confounding interactions that exist between ecosystems, and to leverage them for enhancing marine environmental resilience.

APPENDIX 1

Analysis of publications on the marine environment of Singapore

Research papers on the marine environment of Singapore published from the year 1965 to 2023, regardless of authorship, were compiled from the Web of Science database (https://www.webofknowledge.com). The search terms used were:

“Singapore”

AND

search by site names

“coast” OR “marine” OR “sea” OR “straits” OR “beach” OR “mangrove” OR “mud flat” OR “open water” OR “reef” OR “rocky shore” OR “seagrass” OR “seawall” OR “tidal flat” OR “lagoon” # search by environment type OR “Changi” OR “Coney Island” OR “East Coast Park” OR “Lazarus” OR “Sembawang” OR “Pasir Ris” OR “Punggol” OR “Pulau Ubin” OR “Sentosa” OR “Southern Islands” OR “Semakau” OR “Hantu” OR “Raffles Lighthouse” OR “St. John’s Island” OR “Sungei Buloh” OR “Mandai” OR “Sister’s Island” OR “Jong” OR “Pulau Subar Laut” OR “Pulau Subar Darat” OR “Tanah Merah” OR “Sultan Shoal” OR “Labrador Beach”

AND

search by research area

“climate change” OR "taxonomy" OR “environment” OR “pollution” OR “biodiversity” OR “ecosystem” OR “food” OR “aquaculture” OR “urbanisation” OR “connectivity” OR “biogeography” OR “bioacoustics” OR “virology” OR “microbiology” OR “plankton” OR “bioinformatics” OR “genetics” OR “physiology” OR “behaviour” OR “diversity”

For each of the 5340 publications returned based on the above search criteria, the title and abstract were read in detail. If it was not apparent from the title and abstract that the paper pertained to the coastal and marine environment of Singapore, the entire paper was read briefly.

Papers covering Singapore and other countries (e.g. in Southeast Asia) were included. Review papers directly referencing Singapore’s coastal and marine environment were included, but we omitted general review papers with regional or global coverage that did not directly refer to Singapore. Papers about biodiversity conservation in general (including reviews) were excluded, but those on marine conservation were retained if they also referenced Singapore. Studies on marine-derived food in Singapore were included if relevant, particularly if the animals were sourced locally (e.g. testing for sources of Singapore’s marine-derived food, or genetic analyses on taxa that were also common food in Singapore).

Following the filtering, a total of 1322 papers deemed to be related to the marine environment of Singapore were retained. The papers were grouped by year and in two separate sets of categories—the FRC pillars (Figure 3), and the NRF strategic domains of RIE2025 (Figure A1).

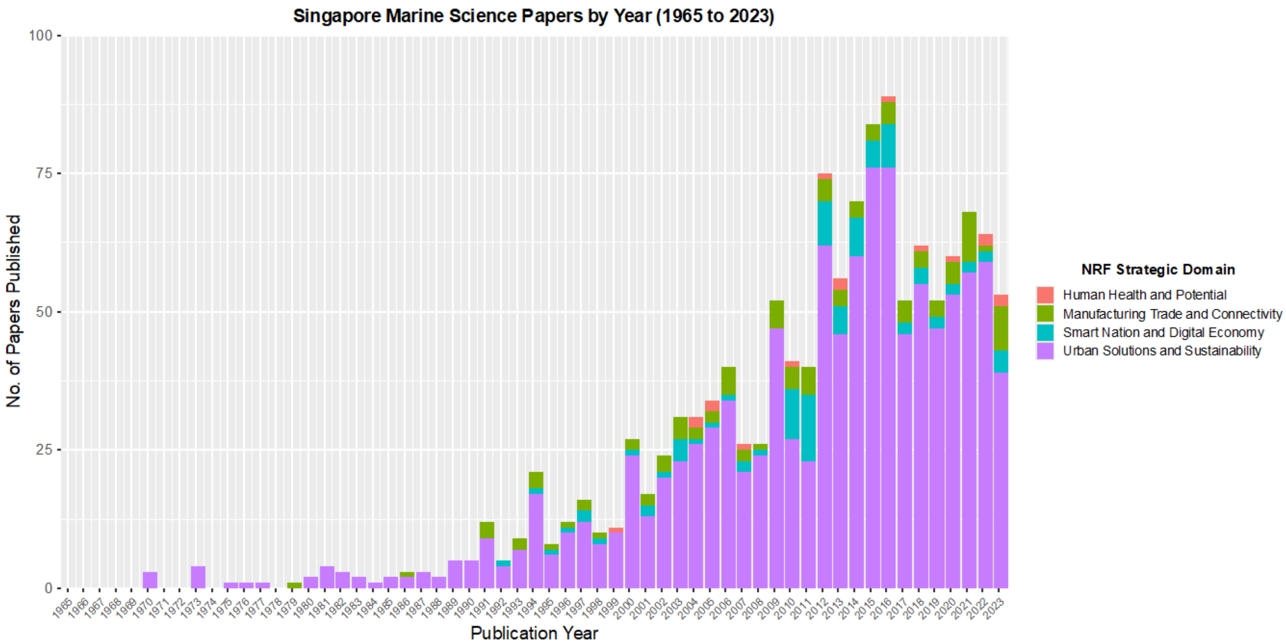

Figure A1. Volume of international peer-reviewed publications on the marine environment of Singapore since independence (1965), categorised based on the NRF strategic domains of RIE2025.

APPENDIX 2

Analysis of marine science research performers in Singapore

Marine science research performers at the PI level based in Singapore, regardless of institution and geographic focus, were compiled from a search of faculty and staff at all university-level institutions. The search was then expanded based on a sample of publications from each researcher to include research performers from governmental agencies and private laboratories. Only researchers who have published in their current capacity in at least the last three years were retained (n=45).

All publications from the Scopus database and analysed by SciVal (https://www.elsevier.com/products/scival) were searched to obtain a global set of marine science papers. Topic clusters of interest were filtered with the keyword "marine":

- Marine Protected Area; Climate Change; Coral Bleaching
- Acoustic Monitoring; Endangered Species; Foraging Behavior (contains topic: marine mammals)
- Holocene; Paleoclimate; Climate Change (contains topic: marine isotope stage)
- Vortex Induced Vibration; Mechanical Vibration; Vortex Shedding (contains topic: marine risers)
- Environmental Monitoring; Plastic Waste; Foraging Behavior (contains topic: marine pollution)
- Harmful Algal Blooms; Acanthamoeba; Eutrophication (contains topic: marine toxins)
- Climate Change; Atmospheric Aerosol; Southern Ocean (contains topic: marine ecosystem)
- Remote Sensing; Coastal Water; Black Sea (contains topic: marine pollution)

All papers published between 2014 and 2023 within those topic clusters were compiled into a single publication set. All SciVal-default institutions globally were ranked based on the Field-Weighted Citation Impact (FWCI) metric computed for the entire publication set. This ranking was the basis of the top 20 institutions presented in Figure 4. The publication set was then split according to the institutions and further categorised into the three FRC pillars—Biodiversity & Nature, Environment & Climate, and Ecosystem Resilience. The FWCI for each institution under each of the three FRC pillars was then computed based on these publication subsets. Publications by the 45 Singapore research performers were pooled into a combined publication set as well as three sets for the FRC pillars to calculate the FWCI for Singapore.

Full names of the top 20 institutions, abbreviated in Figure 4, are as follows. AIMS: Australian Institute of Marine Science; UVSQ: Université de Versailles Saint-Quentin-en-Yvelines; Stanford U.: Stanford University; UTAS: University of Tasmania; ARC COE: Australian Research Council Centre of Excellence for Coral Reef Studies; UBC: University of British Columbia; CSIRO: Commonwealth Scientific and Industrial Research Organisation; Stockholm U.: Stockholm University; UTS: University of Technology Sydney; PML: Plymouth Marine Laboratory; Paris-Saclay: Université Paris-Saclay; ETH Zurich: Swiss Federal Institute of Technology Zurich; OSU: Oregon State University; Columbia U.: Columbia University; UCSB: University of California Santa Barbara; KAUST: King Abdullah University of Science and Technology; UiB: University of Bergen.

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