PRIVATE LIVES

An Exposé of Singapore's Coral Reefs

EDITORS:
Chou Loke Ming ▪ Huang Danwei ▪ Zeehan Jaafar
Toh Tai Chong ▪ Karenne Tun

NUS National University of Singapore | Lee Kong Chian Natural History Museum

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Front and Back Cover: A spawning brain coral *Platygyra sinensis*. **JL**

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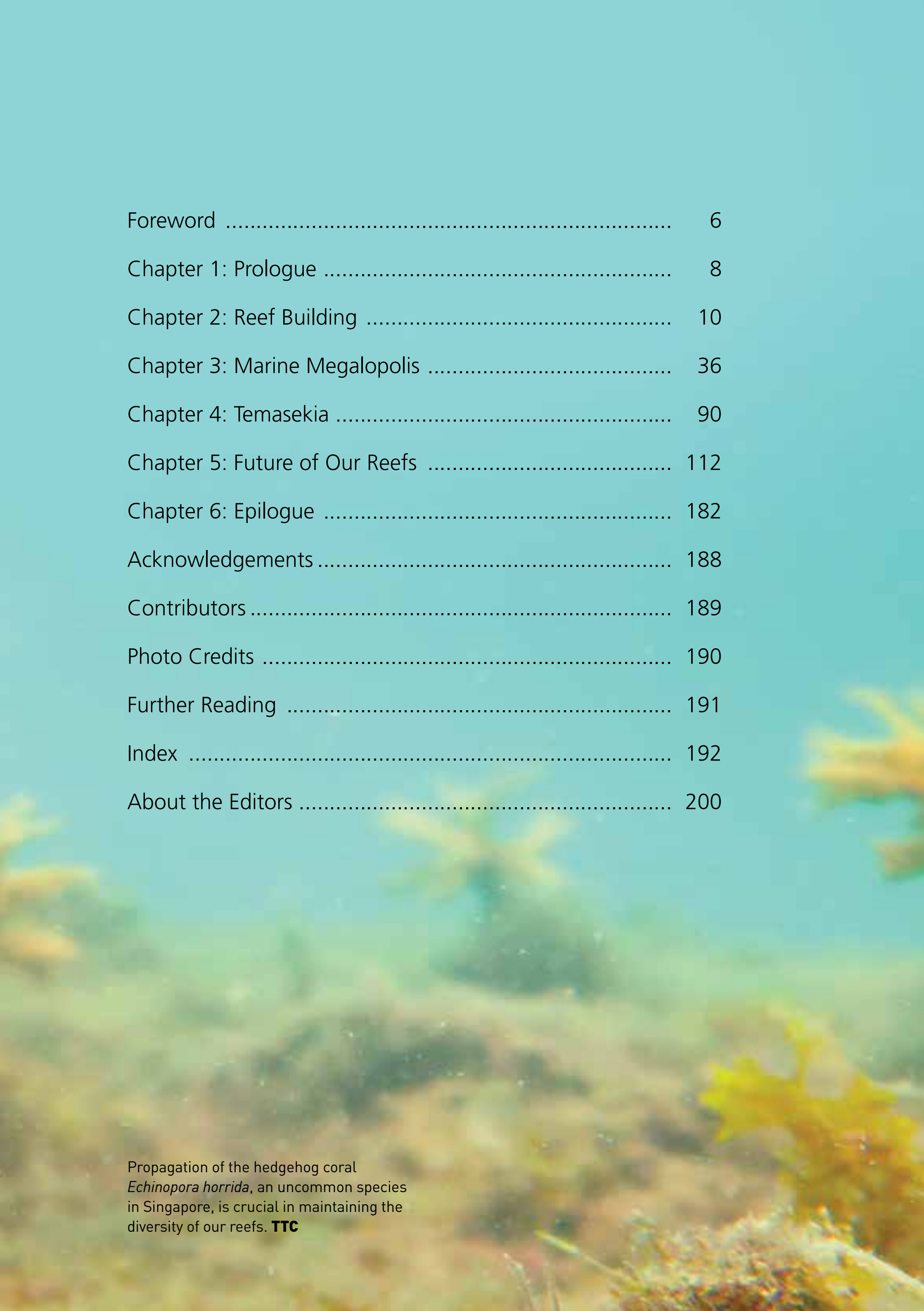


Propagation of the hedgehog coral *Echinopora horrida*, an uncommon species in Singapore, is crucial in maintaining the diversity of our reefs. **TTC**

FOREWORD

Spawning of massive *Platygyra* coral in Raffles Lighthouse. **JL**

I thank the five editors, all of whom are distinguished marine biologists, for inviting me to contribute the foreword for this important and fascinating book about our coral reefs.

I suspect that most Singaporeans, apart from divers, have never seen coral reefs in their natural habitat. Singaporeans who keep aquarium or ornamental fishes may have corals in their fish tanks. Singaporeans will therefore be surprised to learn that there are more than 150 hard coral species in our waters. This is nearly one quarter of the global diversity. We also have 111 species of reef fishes in our waters.

Why should we care about the coral reefs of the world? We should care about them because they host about 25% of all marine species, including fishes. The variety of life supported by coral reefs rival that of the tropical rainforests. For this reason, coral reefs are sometimes referred to as the 'rainforests of the sea' or the 'Amazon of the sea'.

We should also care about the coral reefs of the world because they benefit our tourist industry and they protect us from storms and even tsunamis.

The global picture on coral reefs is a disturbing one. Ten percent of the world's coral reefs are dead. About 60% are at risk due to destructive human-related activities, climate change and oceanic acidification. In Southeast Asia, 95% of our reefs are said to be at risk.

In 2007, the World Wildlife Fund (WWF) launched a project to protect and conserve the global centre of marine biodiversity, consisting of the coral reefs of Indonesia, Malaysia, Papua New Guinea, the Philippines, Solomon Islands and Timor-Leste. The area has been called the Coral Triangle. In 2009, the leaders of the six countries met at a summit in Manado, Indonesia. They adopted an action plan to cooperate to protect and conserve the Coral Triangle. Singapore is not part of the six-nation Coral Triangle Initiative but we can play a positive and active role in this noble effort by protecting our own coral reefs and by helping our neighbours with capacity building and the sharing of our knowledge and expertise. I urge our marine biologists and the Singapore Government to consider doing so.

Professor Tommy Koh
Chairman, Advisory Committee
Lee Kong Chian Natural History Museum,
National University of Singapore (NUS)

1 PROLOGUE

The private lives of coral reef organisms, as illustrated in the pages of this book, show that much can be learned of the way the colourful inhabitants live, grow and interact. These fascinating mysteries can only be revealed for as long as coral reefs exist and stay healthy in our waters. This book adds to the many educational and awareness-raising initiatives that highlight the presence of such a unique habitat in Singapore's waters, so that coral reefs will no longer be obscure to the vast majority of our population. We hope that by showcasing these remarkable creatures, we would generate a wider appreciation of the habitat and its exclusive beauty. It is for this purpose that the coral reef habitat has been selected as a natural heritage for in-depth exposure in the *Private Lives* series.

We would like to take this opportunity to thank friends of the reef for enriching the book with their knowledge, observations and pictures. They have spent much time watching and capturing significant aspects of Singapore's reefscape. These contributions are precious sources of information that offer insights to the otherwise elusive behaviour of reef organisms. The body of knowledge on Singapore's coral reefs is stronger for them.

On a sad note, we bid farewell to Dr. Sin Tsai Min, who lost the battle with cancer during the preparation of this book. Tsai Min tirelessly contributed towards coral reef science and conservation, as well as towards this book. We celebrate her life work and dedication towards coral reef research in pages 180-181.

We are extremely fortunate to have such an ecological wonder that is our natural heritage right at our doorstep. It is important that we collectively steward the imperiled but resistant habitat to a successful future. As editors, we hope that the work we present inspires you to share the wondrous private lives of Singapore's coral reef organisms with everyone.

Black axil chromis *Chromis atripectoralis* at Pulau Satumu. **JL**

2 REEF BUILDING

Hard corals make up the main framework of the reef ecosystem. **HD**

HOW OLD AND WHERE ARE THEY?

Singapore's coral reefs developed after the last glacial period or ice age as melting ice raised sea levels to what they are today. The low sea-level period occurred about 10,000 years ago, when what we now know as the seafloor between Singapore and Jakarta was dry land. As the sea level rose, flooding of the exposed land increased the area of shallow seas that favoured the establishment of coral reefs and their development into specialised, productive habitats that support incredibly rich biodiversity.

Illustration of a coral reef. **TYC**

Singapore's coral reefs host a multitude of flora and fauna. **TCH**

The reefs continued to thrive in Singapore's clear, shallow and warm waters right through the country's early 13th century founding by Prince Sang Nila Utama from Batavia and the 1819 founding of modern Singapore by Stamford Raffles. Coral reefs grew over the centuries and persisted with the country's transformation from a small backwater trading settlement to one of the world's busiest ports. They were exposed to large changes in the marine environment especially from the 1960s when the pace of development accelerated and intensified. The reefs have persevered against a complexity of environmental challenges.

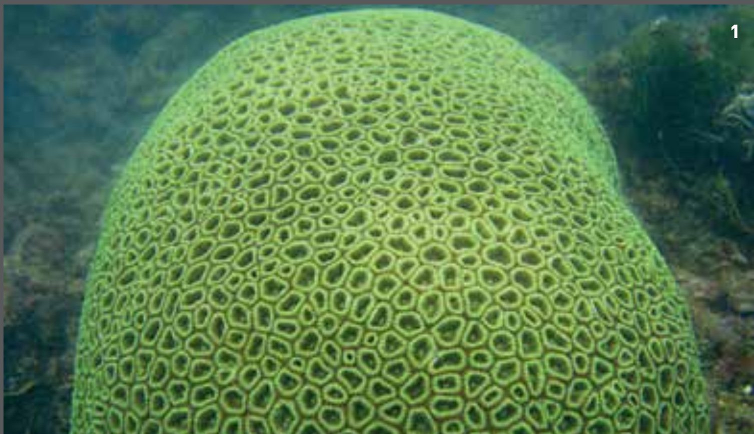
Singapore's coastal areas have been extensively modified since the 1950s. **KT**

Up until the 1960s, coral reefs were found fringing almost all of the southern offshore islands and several offshore islands nearer the east and west openings of the Johor Strait. Reefs with extensive reef flats fringed the mainland especially along the south-western coast. Almost all reefs on the mainland, except for a small patch at Labrador beach, were reclaimed for land expansion. The reef flats of some of the southern offshore islands were also reclaimed. Jurong Island for example, is an amalgamated landmass of several original islands. All the fringing reefs of the original component islands are now buried under sand so that the islands are merged into a single large island. Today, most of the reefs are found in the southern offshore islands.

Satellite image of Singapore's southern coastlines in 1984. **Gorelick et al. 2017**

Coral biodiversity origins

In 2004, scientists discovered that corals in the Pacific and Atlantic Oceans evolved millions of years ago. Several studies following that, including some on coral colonies in Singapore, showed that there are more species with distinct inter-relationships than previously thought. Corals traditionally in the genus *Favia* were initially considered closely related because walls in their individual skeletal units, or corallites, are separate. We now know that they are actually derived from many



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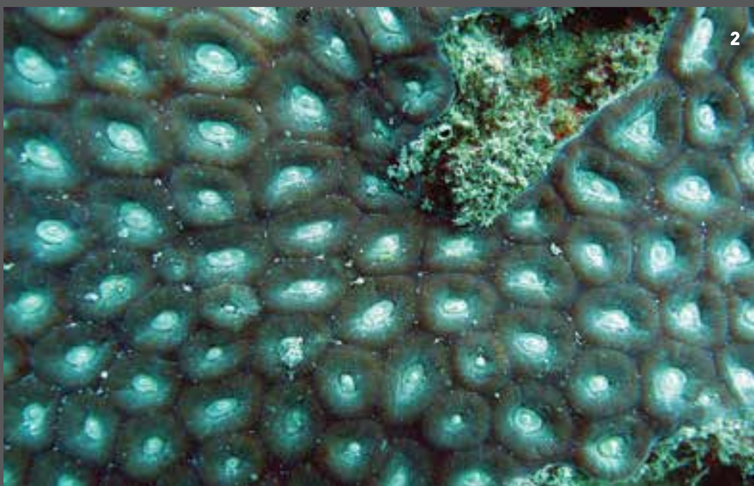


2

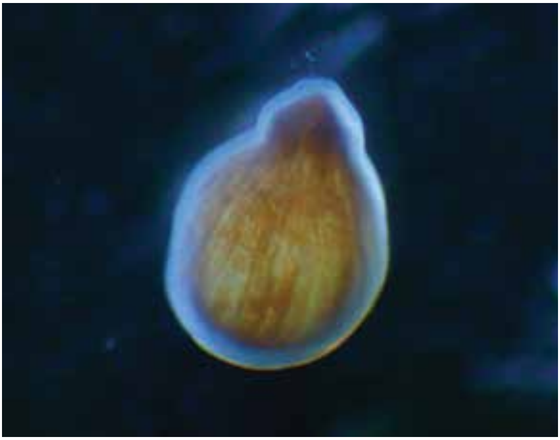
distinct lineages, including some that are restricted to the Atlantic Ocean. Three distinct *Favia* lineages are found in Singapore, and among them *Dipsastraea* is more closely related to the free-living *Trachyphyllia* than it is to *Favites* and *Goniastrea*! **HD**

Dipsastraea lizardensis (1), *Favites rotundata* (2) and *Goniastrea stelligera* (3) were misclassified as *Favia*, but the former is actually most closely related to the free-living *Trachyphyllia* (4). **HD**

BUILDING BLOCKS POWERED BY ALGAE

Some of the smallest living organisms are responsible for the large expanse of coral reefs. Within animals such as corals, sea anemones, sponges, and some bivalves and flatworms, lives zooxanthellae. Informally known as zoox, these are single-celled algae of the family Symbiodiniaceae. These cells are present in large numbers within their respective host animals, and power the entire ecosystem by making food with sunlight and inorganic nutrients — wastes contributed by their hosts.

Coral reefs are one of the most productive ecosystems. **DHI**

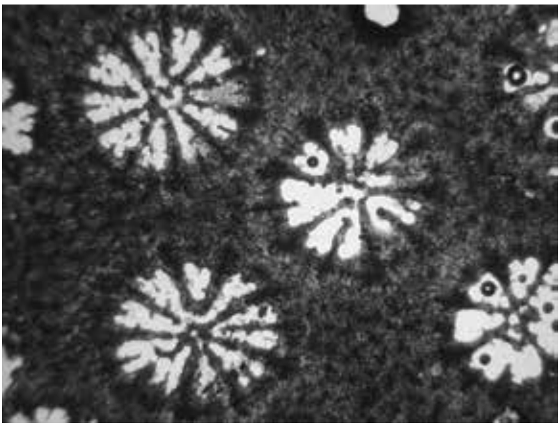


Newly released larvae of *Pocillopora acuta* with brown zooxanthellae symbionts living within coral tissues and providing nutrients for the host. **LCS**

Coral animals that build coral reefs do so using their external skeleton made of calcium carbonate (limestone). These tiny sea anemone-looking individuals are carbon copies which together form one colonial animal. Corals are almost entirely dependent on their symbiotic zooxanthellae for nutrition. The energy that is extracted from this nutrition is used by the coral hosts to produce and secrete limestone around its tissues.

Corals make use of their tentacles to capture prey items. **HD**

The cellular process of laying down the calcium carbonate skeleton is therefore intricately linked to the host-symbiont relationship. In this way, colonies of corals build their skeletons upwards and outwards while occupying the top layer of the limestone, forming the magnificent structures of the coral reef.



The calcium carbonate around coral polyps protect these soft tissues from mechanical damage. **HD**

Skeletal secrets

Coral polyps are soft, gelatinous organisms, highly vulnerable to injury from abrasive forces and hungry predators. The polyps secrete a calcium carbonate skeletal framework upon which new tissue is laid and from which mechanical strength is obtained. The plating, branching and boulder-like colonies collectively form complex structures that serve as essential habitat for a wide variety of reef organisms.

Although some corals may appear simple in structure, their skeletal features are anything but simple when observed in fine detail. Every species has a unique combination and intricate arrangement of skeletal elements — information that is used to distinguish one species from another. Other characteristics of the coral skeleton, for example growth bands, can also help us understand how corals develop and grow. **LN & DW**

Branching *Acropora* provides suitable shelter to numerous species of small fishes and crustaceans. **DW**

The large teeth-like structures of *Lobophyllia* are usually obscured by thick fleshy polyps. **DW**

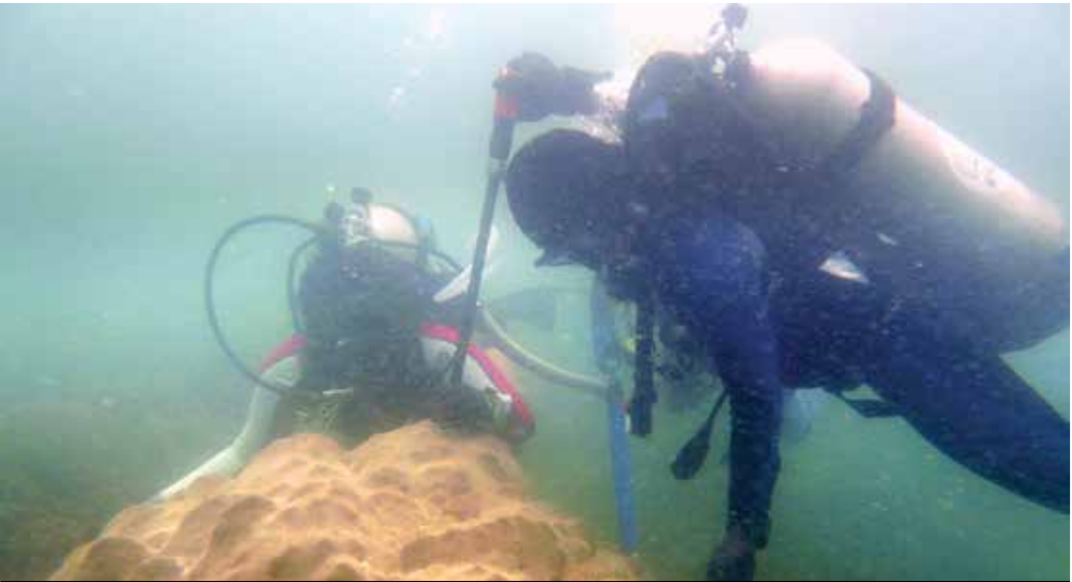
Narrow ridges and valleys run parallel to the edges of a *Pachyseris* skeleton. **DW**

Fine projections among the corallites of this *Echinopora* skeleton gives it a hairy appearance. **DW**

Clues from coral cores

Corals are animals that build reefs using their external skeleton, which is made of calcium carbonate. As corals calcify over time, new layers of calcium carbonate are laid on top of the existing skeleton. The incremental layers of skeleton provide a chronology for determining age and growth rates of the coral colony. The chemical composition of each layer also contains records of trace elements at the time it was laid, and can be used to reconstruct the environment at the time in which the corals lived.

A massive *Porites* coral colony (Malaysia) estimated to be about 400 years old. These corals usually grow between 1 to 2 cm per year. **JT**



Scientists carrying out coring of a massive *Porites* coral. Coring does not cause long-term harm to the coral colony, and core holes are plugged to facilitate recovery. **JT**

Cores taken from long-lived corals, such as those from *Porites* species, reveal incremental growth layers that show up as luminescent bands when exposed to ultraviolet light, or as density bands when X-rayed. The study of these growth layers or bands is called sclerochronology, and is similar to the study of growth rings in trees. Current applications include reconstructing historical land-based sources of pollution, and assessing historical coral growth in relation to environmental changes. Skeletons of other calcifying organisms, such as giant clams and sea fans, can also be used for sclerochronology. **JT**

Bands in massive *Porites* coral visualised using ultraviolet (UV) light (top) and X-ray (bottom) to show the chronology of the incremental growth layers. One bright and dull UV luminescent band couplet, or one high and low density band couplet is equivalent to one year's worth of coral growth. **JT**

BASIC CONSTRUCTION PLAN: SIMPLE YET COMPLEX

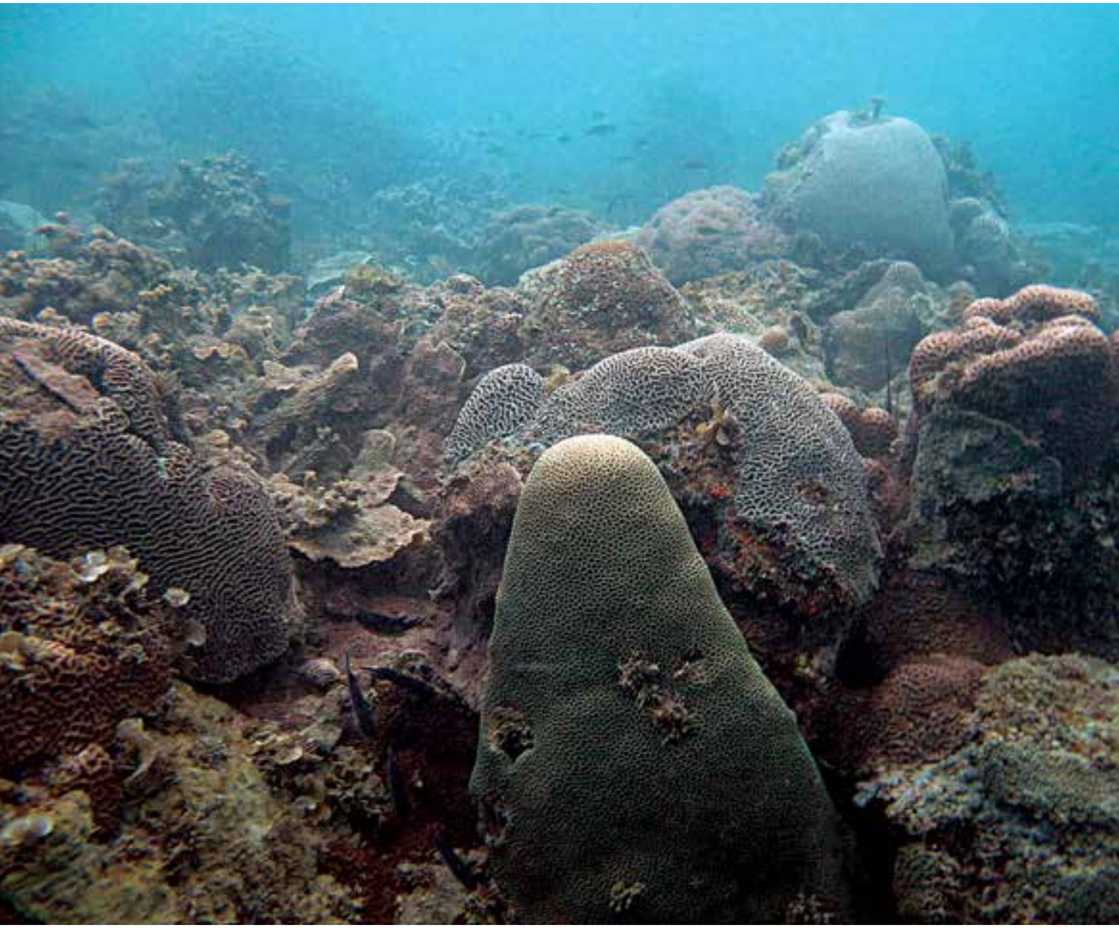
Singapore is situated along the Malacca Straits, a relatively shallow region of the Sunda shelf. Corals here construct shallow fringing reefs rather than the large barrier reef along continental margins such as Australia's Great Barrier Reef. In the past, fringing reefs formed a perimeter around Singapore's mainland and many of the 46 offshore islands. These areas continue to decline as more islands are joined by reclamation. Patch reefs such as Cyrene Reefs are corals that formed around raised seabed and are exposed when the tide is low.

Singapore's reefs can generally be subdivided into three zones. The shallowest area, the reef flat, usually continues seaward from the shoreline. During low tide, parts of the flat are emerged and exposed to air, as well as sunlight in the day. Here we find boulder-shaped corals, sponges, zoanthids and other invertebrates that tend to live within pockets of depressions along the reef profile that would still be submerged. Available space on rocks are covered by algae of multiple kinds, as grazers such as sea urchins mow them down, joined by herbivorous fishes during high tide.

Patch reefs such as Cyrene Reefs, form around submerged islands, and are exposed when the tide is low. **HD**

Crevices found in reef flats form natural habitats for marine organisms. **HD**

The reef crest joins seaward from the flat. This is often the richest zone on a reef, represented by the most diverse assemblage of corals of all shapes and sizes. The crest confronts most of the wave action arriving from offshore, and is therefore the zone that first receives larvae from adjacent reefs. Corals pack this zone densely, competing with one another for the limited space. Living among these corals are many other invertebrates. Sessile inhabitants include sea anemones with their symbiotic anemone fishes, sponges and sea squirts. Roaming the reef crest amidst the complex topography are animals that often hide in crevices such as shrimps, crabs, shells, crinoids and cuttlefish. Hovering over the reef are the richest assemblages of fishes in the marine environment — from herbivores such as parrotfishes and damselfishes, to carnivores like groupers and snappers, and top predators such as sharks.



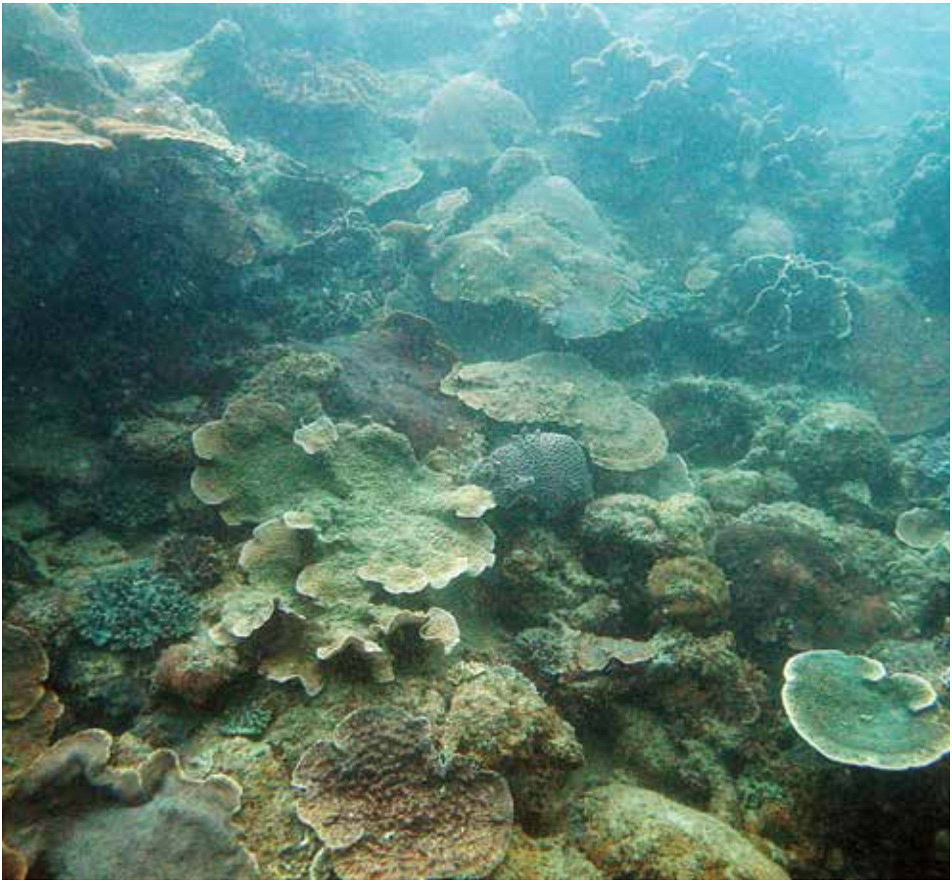
The reef crest slows down incoming waves and reduces the speed of the water reaching the shore. **HD**

A pink skunk anemonefish *Amphiprion perideraion* and its host sea anemone *Heteractis magnifica.* **JL**

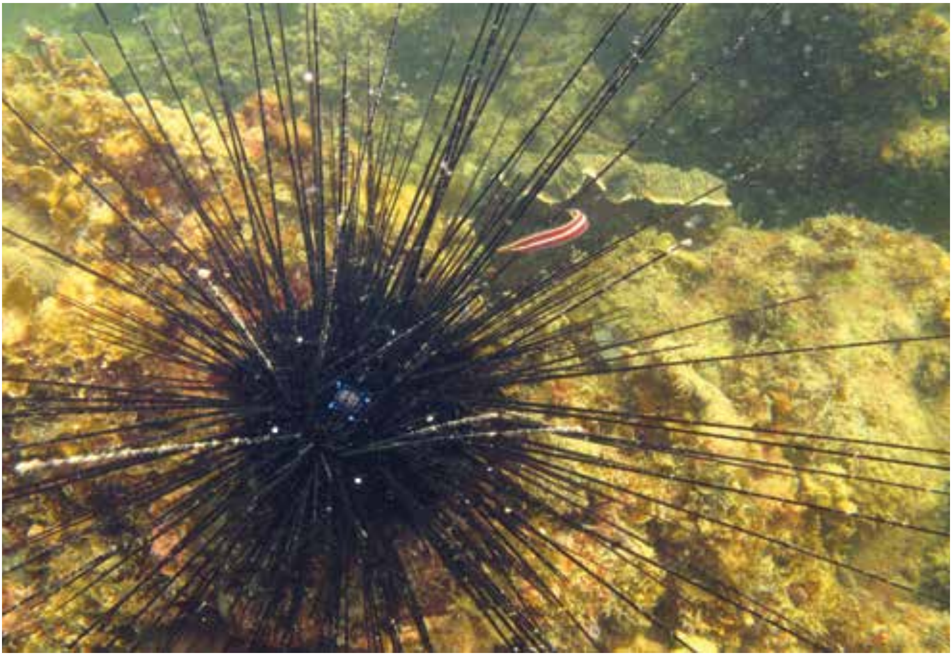
This pygmy squid *Idiosepius* sp. was observed in Pulau Hantu. **JL**

This sea squirt *Ascidia gemmata* has distinct red stripes that are only found on the oral siphon. Some ascidian species can also host small amphipods. **JO & YW**

The reef slope curves downwards from the crest, losing light intensity with increasing depth. The density of organisms dwindles down the slope, but plating corals may dominate, spreading horizontally to capture light that has managed to penetrate to this depth.



At the base of the reef slope, plating corals increase their surface area to maximise light capture for the photosynthetic zooxanthellae. **HD**



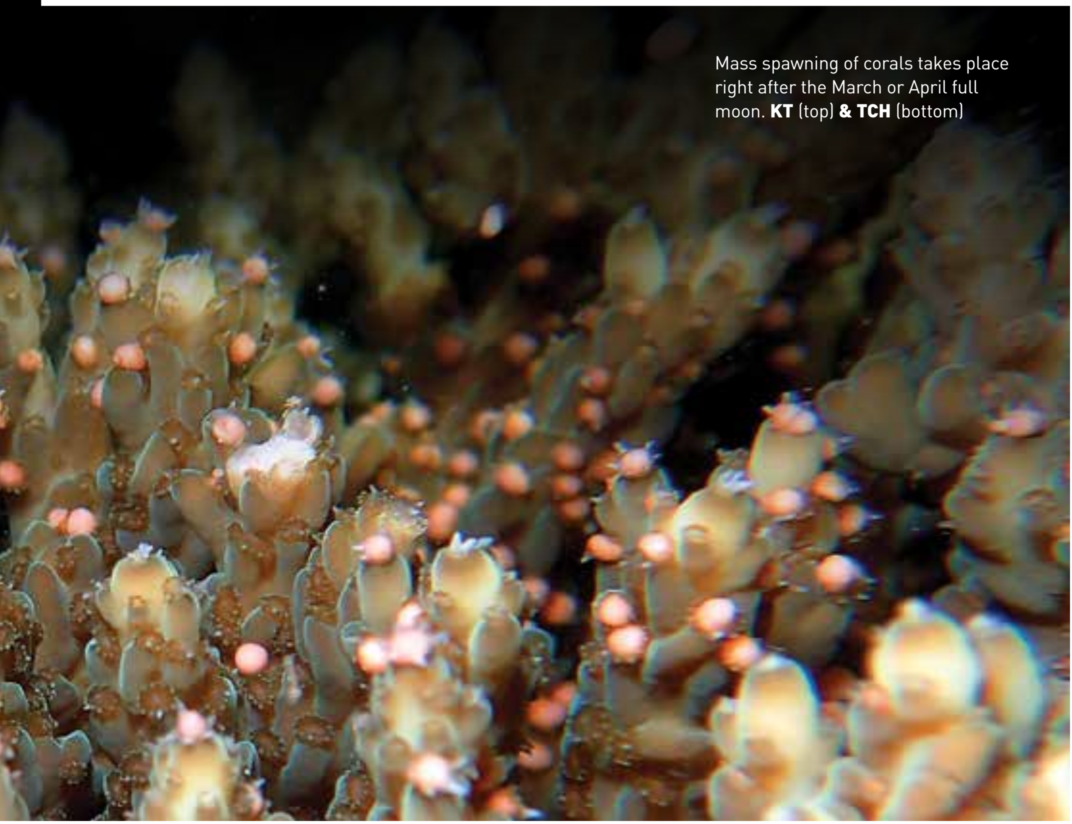
The needle-spined sea urchin *Diadema setosum* and its symbiont urchin clingfish *Diademichthys lineatus*. **JL**

In Singapore, at depths 6 to 8 m, corals are barely receiving sufficient sunlight for the zooxanthellae to make food. Some plating corals and free-living mushroom corals, as well as sponges, are scattered amidst coral rubble, sand and silt. The adjoining seafloor — silty and dark — slopes gently downwards from about 8 m, and harbours the occasional sea fan, sea whip, sea urchin, as well as a few species of corals that do not associate with symbiotic algae.

Sea whips from the family Ellisellidae can live at greater depths within the reef as they are less dependent on sunlight. **HD**

Mass coral spawning

Most corals reproduce by releasing, or ‘spawning’, their egg bundles into the water for fertilisation in the water column. For many years, coral spawning was thought to be confined to geographical regions at higher latitudes that experience large seasonal variations in temperature and other environmental factors. Studies to examine the reproductive cycles of corals in Singapore began in the year 2000. Despite the predictions that effects of seasonality would be low in equatorial locations, scientists at the Reef Ecology Laboratory in the National University of Singapore (NUS), found that most corals have clear seasonal reproductive cycles and that there was considerable overlap in spawning times among species. Large multi-species coral spawning events were first observed in 2002 and have been documented in most years since. These events occur after the March or April full moon and 70 species have been documented to participate. The discovery was one of the first to show that mass coral spawning occurs on equatorial reefs, even in the absence of large seasonal environmental fluctuation. **JG**



Mass spawning of corals takes place right after the March or April full moon. **KT** (top) **& TCH** (bottom)

3 MARINE MEGALOPOLIS

Coral reefs are bustling with activity. **DT**

TURF WARS: SMALL SCALE, BIG IMPLICATIONS

On any coral reef, there is always more that's happening than meets the eye. Territorial boundaries are constantly being disputed despite the apparent serenity. Some of these territorial battles occur at a very small scale and requires patience and a keen eye to observe. Try spotting the following reef inhabitants the next time you visit a reef.

The Titan triggerfish *Balistoides viridescens* can be highly territorial and aggressive. **ZJ**

TITANS OF THE REEFS

Triggerfishes are extremely territorial especially when defending their nests. However, none are more feared that the Titan triggerfish (*Balistoides viridescens*). This fish is aggressive when it perceives a threat within its territory. Other reef fishes and divers have been chased away when they get too close to the nests of these Titans. The nests are generally cone-shaped and constructed in a sandy area of the reef. As Titans are one of the largest species of triggerfishes, they can cause significant cuts and bruises when they commit to an attack. Some Titans have also resorted to biting the scuba gear of divers in an effort to drive them away.

DAMSELS IN DISTRESS

Some damselfishes (family Pomacentridae) are known as the gardeners of coral reefs. They tend to specific areas where they selectively remove unwanted algal species in order to encourage growth of preferred species. By doing this, damselfishes are aiding select species in their turf wars, leaving little chance to unfavoured species to colonise the area. Damselfishes are also territorial at and around their garden patches and when distressed by unwanted guests, will chase the intruders away.

Damselfishes, like the smoky damsel *Pomacentrus littoralis*, farm algae on the reef to propagate algae species that they prefer. **JL**

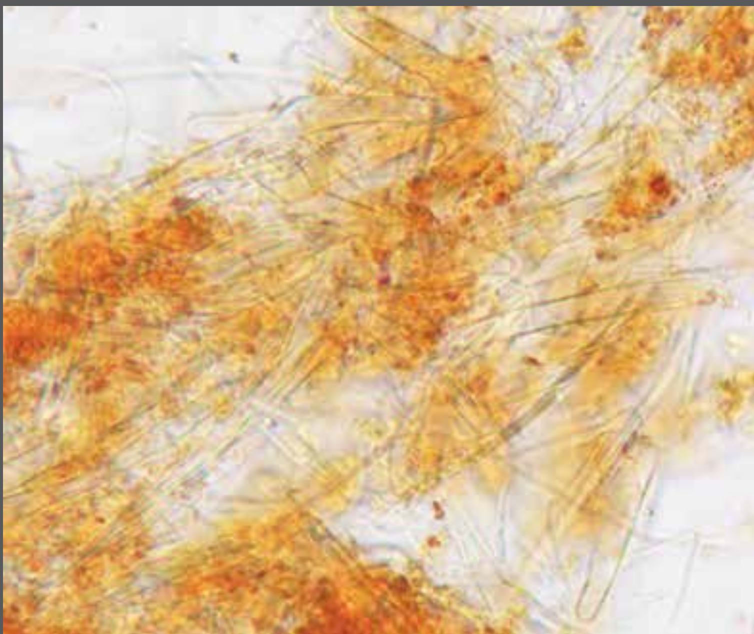
Inch wars: kill or be killed

Coral reefs are highly-populated areas and coral species have the ability to grow to extremely large sizes. Hard corals compete for precious light-capturing spaces within coral reefs. What happens when growth expansion of two neighbouring species cause them to come into close contact? They do not stop growing but engage in chemical warfare to kill competitors at their edges! Fast-growing branching coral species from

A band of bleached (left) or dead (right) tissue between two coral colonies resulting from competition for space. **SWT & ARR** families Acroporidae and Pocilloporidae grow over adjacent colonies. Those from families Merulinidae and Meandrinidae expel digestive mesenterial filaments from their gut to digest their neighbours. Some species of *Platygyra* deploy sweeper tentacles that can extend up to 10 times the length of their feeding tentacles, to kill their competitors. Whichever the strategy, one thing is for sure — only the fittest survives. **SWT & ARR**

Born with weapons

Unique to all members of Cnidaria — corals, sea anemones, and jellyfishes — are tiny capsules that ensnare prey, fight off competitors, and defend against threats. These capsules, manufactured within specialised cells, harbour a coiled barbed thread that explosively discharges when an appropriate stimulus is received. Three types of capsules are known — nematocysts, spirocysts and ptychocysts. Nematocysts, present in all cnidarians, sting and deliver venom to weaken the victim. Spirocysts, found only in corals and sea anemones, do not contain venom. Ptychocysts, distinct only to tube anemones, neither sting nor contain venom; instead these capsules weave mud sleeves that the animal hides in when threatened. **NY**



Nematocysts extracted from the tentacle tip of the sea anemone *Actinostephanus haeckeli*. **NY**

Types of capsules found in the burrowing sea anemone *Metapeachia tropica*. Spirocyst (far left) and nematocysts. Note here there are many different forms of nematocysts. Scale bar = 20µm. **NY**

Discharged and intact nematocysts; the arrow indicates a barbed thread already discharged; stars indicate intact nematocysts. **NY**

LOVE THY NEIGHBOURS: INHABITANTS OF A BUSTLING ECOSYSTEM

The healthy coral reef is a busy ecosystem, not unlike a marketplace. Anyone who has dived or snorkelled at a coral reef can attest to the diversity and abundance of species that are associated with this habitat. Many scientists believe that overcrowding in healthy reefs contributes to the abundance of specialisations among reef organisms. Groups of species of these specialist organisms perform a function unique to them but are complementary to others to sustain the ecosystem. Here are some examples of how organisms survive the space squeeze.

The blue line grouper *Cephalopholis formosa* waits for prey amongst the dense coral growth at Pulau Satumu. **JL**

The slender bodies of the green clown goby *Gobiodon histrio* help them weave in and out of branching corals easily. **JL**

CONDOMINIUM PROJECT

Branching corals such as species of *Acropora* and *Pocillopora* are akin to condominiums. Within the tight spaces between the arms and branches of these corals exists an entirely different world often not observed by the casual diver. Associated with branching corals are species of shrimps, crabs and fishes that spend their entire adult lives within these tight spaces.

Coral gobies (*Gobiodon* and *Paragobiodon* spp.) are thin and disc-shaped. When viewed from the sides, they are broad but when viewed from above, they are so thin that they are hardly seen. The distinct shape of these fishes helps them manoeuver the tight spaces within the branching corals where they seek shelter. The host corals compete for space in the reefs with other corals and algae. Scientists have found very recently that at least one species of branching corals releases chemicals that cue the coral gobies to eat the competing algae. Apart from protecting its home, the gobies also receive chemical defence from toxins present in the algae.

Commonly present within the arms of branching corals are the white coral crab (*Tetralia nigrolineata*), red coral crab (*Trapezia cymodoce*) and the *Acropora* snapping shrimp (*Coralliocaris graminea*). These small but feisty crustaceans protect the host corals by nipping at coral predators such as crown-of-thorns starfish, some coral-eating fishes and slugs when they come too close or threaten to consume the corals.

The coral crab *Tetralia nigrolineata* is territorial and helps defend its host coral *Acropora* sp. from predators. **JL**

Developing egg of the cuttlefish *Sepia latimanus* between the branches of a *Porites* coral at Pulau Hantu. **JL**

Reef organisms also utilise arms and branches of corals as sites for egg deposition. Often these eggs appear as masses, or part of a long coiling tape. Eggs are at times tended to by either, or both, parents; but often, once laid, the eggs are left to develop on their own.

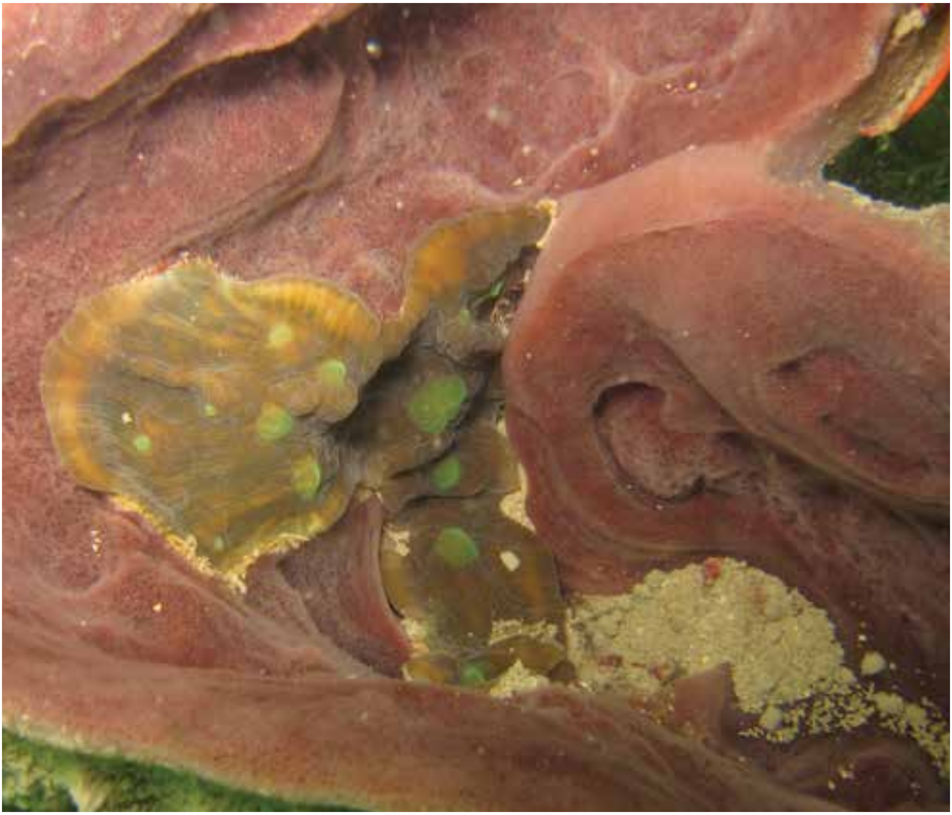
Guardian of the corals

Coral crabs (*Trapezia* spp.) reside in the crevices and between branches of corals. These crabs feed on coral mucus and sediment on the surface of the polyps. They are small but aggressive, and can guard their host against larger predators by nipping at them. The only two species of *Trapezia* found in Singapore — *T. cymodoce and T. septata* — associate with cauliflower corals (*Pocillopora* spp.). **KYP**

Trapezia cymodoce defending its coral host *Pocillopora acuta* off Kusu Island. **KYP**

SPONGE SHELTERS

Some organisms are specialised to live their entire adult lives within the pores of sponges. Scientists working on these organisms affectionately, and quite literally, refer to them as 'spongers'. Water currents are generated within the channel system found in sponges, thus bringing food in the form of small particulate matter to the organisms residing within. Amongst the pores of some sponge species reside organisms such as snapping shrimps (*Synalpheus* spp.), amphipods (Amphipoda), isopods (Isopoda), brittlestars (Ophiuroidea), as well as flatworms (Nemertea) and bristleworms (Annelida).



Like corals, marine sponges such as *Xestospongia testudinaria* also provide habitats for other organisms, including corals! **JL**

TIME SHARING

In an overcrowded ecosystem such as a coral reef, the use of space can be maximised temporally and indeed, this is exactly what happens. Reefscapes appear very different during the day and night as different organisms become active. During the day, colourful fishes abound. Most common in our reefs are butterflyfishes (Chaetodontidae), damselfishes (Pomacentridae) and groupers (Serranidae).

Nightfall, in turn, sees diurnal (day-time) species taking refuge to rest and stay safe from predators. Some species of parrotfishes (Scaridae) even produce a cocoon to rest in at night. The cocoon, made from mucus secreted by the fish, is thought to mask its scent from nocturnal (night-time) predators such as moray eels.

The brick soldierfish *Myripristis amaena* is active at night. **JL**

Other common nocturnal fishes in our reefs include squirrelfishes (Holocentridae) and cardinalfishes (Apogonidae). Nocturnal fishes often sport reddish hues, which appear dark under low light conditions. This aids them as they shelter under large rocks and between large corals during the day. They also have disproportionately larger eyes which help them see better at night. Under cover of darkness, these fishes readily leave the safety of their shelter to feed. Similarly, crustaceans such as crabs, lobsters and shrimps leave their shelters at night to look for food.

A surf parrotfish *Scarus rivulatus* sleeping under the cover of a rock. **JL**

The *Sargassum* paradox

High algal biomass typically results in reefs shifting from hard coral to macro-algal dominated communities. The upper reef zones in Singapore however, remain intact despite the abundance of several *Sargassum* species — the dominant *S. ilicifolium*, as well as four other species: *S. granuliferum*, *S. aquifolium*, *S. swartzii*, and *S. polycystum*.

Herbivores such as sea urchins, rabbitfishes, and surgeonfishes that typically feed on these brown algae are low in diversity and abundance in Singapore's reefs. With the seeming lack of biological controls, is the distribution of *Sargassum* then limited by physical and environmental factors? What are the effects of the large biomass of algae on corals and the reef system? Answers to these questions can help scientists better understand coral-algae interactions in light of global climate changes. **JL**

Sargassum can dominate reef environments. **JL**

TIES THAT BIND: PARTNERSHIPS IN THE SEA

Biological associations between organisms have long fascinated humans. In trying to understand the workings of the natural world, scores of scientists have sought to document and understand how associations between organisms contribute to the ecosystem. In and around coral reefs, these associations abound, ranging from partnerships where both parties benefit to those where one flourishes to the detriment of another. A healthy coral reef ecosystem supports many forms of associations. So ubiquitous are these associations that scientists have acknowledged them to be integral to the health of coral reefs. A coral reef threatened by natural or human-induced causes beyond its tolerance threshold will cause these associations to fail, and will ultimately spell trouble for the ecosystem. Teams of scientists are presently still making progress in deciphering how these associations are regulated and the factors that influence these partnerships. Here, we take a peek at a world unseen from above the water surface, where unlikely species form interesting coalitions as they go about their daily lives.

Singapore celebrates associations between species in our reefs by the Care-for-Nature Stamp Series. (Reproduced with permission from Singapore Philatelic Bureau)

SYMBIODINIACEAE TO RULE THEM ALL!

In the earlier chapter, we learnt that many species of corals associate with species of zooxanthellae from the family Symbiodiniaceae. These symbiotic algae live within the host tissue in very high densities. Other than corals, some species of sea anemones, shells, jellyfishes, sponges and flatworms also harbour zooxanthellae. Once within their host, these algae can photosynthesise, and provide extra sources of nutrients to their hosts.

Symbiodiniaceae algae can be found in sea anemones, corals and giant clams. Here, a newly settled *Pocillopora acuta* coral larva has zooxanthellae in its tissue. **LCS**

THE MOBILE LANDLORDS AND THEIR TENANTS

Many smaller organisms in the coral reef are found in association with larger ones. The larger organisms, the landlords, provide shelter to their smaller tenants.

The long stinging tentacles of the jellyfish are a sure way to keep predators at arm's length. For this very reason, several species of juvenile trevallies and jacks (family Carangidae) are often found seeking shelter within and around the bells, as well as between the tentacles, of jellyfishes. Once they are larger however, these fishes will abandon the safety of their tentacular landlord to range freely in the reef.

Jellyfishes like *Cyanea* sp. are notorious for their stings but some fish species can hide among the tentacles for protection. **JL**

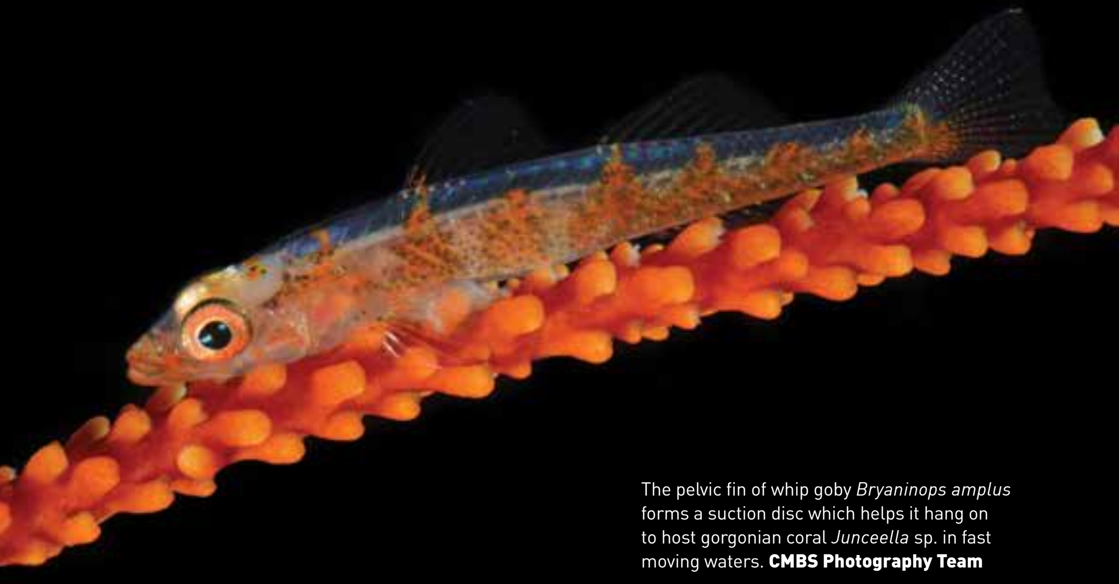
HIDDEN IN PLAIN VIEW

Some tenants are associated with their hosts throughout their adult lives. In such cases, these organisms are often well camouflaged to match the colour and texture of their hosts.

The sea pen porcelain crab (*Porcellanella picta*) is one such example. It lives within the arms of the sea pen, an animal closely related to sea anemones and corals.

The sea pen *Pteroeides* spp. is related to corals and sea anemones and it is the permanent home for adults of the porcelain crab *Porcellanella picta*. **KYP**

Whip corals (*Junceella* spp.) often grow in areas with strong currents. As these corals filter food from the water column, it is believed that growing in conditions with fast water flow will aid their quest for food. So how do whip gobies (*Bryaninops* spp.), an associated species of fish, remain on the whip corals in the fast-flowing waters? The pelvic fins of these fishes, located above the belly, form suction cups that help them to hang on. This ensures that the fishes can move easily over the whip corals. While looking for the whip gobies, you might come across the saw-blade shrimps (*Tozeuma* spp.) that also spend much of their day on whip corals.



The pelvic fin of whip goby *Bryaninops amplus* forms a suction disc which helps it hang on to host gorgonian coral *Junceella* sp. in fast moving waters. **CMBS Photography Team**

So similar are the patterns of the crinoid squat lobster (*Allogalathea elegans*) that it is difficult to see where it is when on its feather star (also known as crinoid) host. These small crustaceans live around the host's mouth region and are known to take morsels of food particles bound for the mouth of the host.

The crinoid squat lobster *Allogalathea elegans* lives near the mouth of the feather star *Pontiometra andersoni*. **JL**

Spindle snails (family Ovulidae) are common in the reefs of Singapore, but are especially difficult to see. These snails live on gorgonian corals (*Muricella* spp.) where their mantles, the soft part of their bodies usually wrapped over the shell, closely resemble that of the host. These snails feed on the gorgonians thereby ingesting the pigments of the host, which are then transferred to their shells and tissues. When moving from one host to another, the snails can change colour as they assimilate the pigments of the new host.

This spindle snail *Phenacovolva rosea* is well-camouflaged on its host sea fan *Echinogorgia* sp. Spindle snails feed on the pigments of their host gorgonians, integrating the pigments into their shell. **JL**

THE LIVING 'INVISIBLE CLOAK'

Some reef organisms 'disappear' when they adorn themselves with living accessories found around them. It is near impossible to spot these animals once they have their invisible cloaks on.

The sponge crab (*Tumidodromia dormia*) tailors sponges and tunicates to fit over its shell. The piece of sponge or tunicate is then carried around by the last pair of legs, modified for this purpose. Once under the 'cloak' the crab goes about its daily business while being shielded from the prying eyes of predators.

The sponge crab *Tumidodromia dormia* sticks sponges and tunicates on its shell, which helps it blend with the surrounding. **JL**

The velcro decorator crab (*Camposcia retusa*) picks different organisms from the reef and adheres them to itself. Common organisms used are zoanthids, algae and sponges. These stay on due to the tiny hooks on the crab's body. Some of these organisms continue to grow while attached to the crab. Once this patchwork 'cloak' is complete, the crab is difficult to observe as it moves extremely slowly and resembles the surrounding reef.

The velcro decorator crab *Camposcia retusa* with bits of material gathered from the reef on its carapace (top) and the same individual with the material removed (bottom). **CMBS Photography Team**

THE HARD-OF-SEEING, THE WATCHMAN AND THE FREELOADER

Several species of snapping shrimps (*Alpheus* spp.) are excellent homemakers. They make sturdy burrows within the seafloor and maintain the burrows periodically. These shrimps have poor eyesight but their partner fishes, the watchman gobies (*Amblyeleotris* spp. and *Cryptocentrus* spp.) make formidable security guards. The watchman gobies position themselves at the entrance of the burrows, and when they are both outside, the shrimp and the goby partners stay in constant communication. How do they do this? What is not easily seen is that the shrimp ensures at least one of its antennae stays in contact with one of the goby's fins. At the first sign of a threat, both partners make a quick dash into the safety of the burrow.

The watchman goby *Cryptocentrus sericus* positions itself at the burrow entrance of a snapping shrimp *Alpheus* sp. **JL**

At times, the goby and shrimp partners have company. The blue-tailed dartfish (*Ptereleotris hanae*) often seeks refuge in the burrows of the goby and shrimp. The dartfish hovers about half a metre above the seafloor, feeding on zooplankton within the water column. The dartfish has never been observed to participate in the association of watchman gobies and snapping shrimps. However, when danger approaches, they are the first to zoom into the burrows.

TONGUE-TIED

Isopods are crustaceans closely related to crabs and shrimps. The parasitic isopod (*Cymothoa exigua*) finds a host fish, eats away its tongue and subsequently lodges itself where the host's tongue used to be. Scientists are still uncertain as to what this parasitic isopod feeds on. Some suggests that it feeds on the morsels of food that the fish consumes while others believe that the isopod feeds on the blood of the fish.

Do you wonder how these crustaceans reproduce while being lodged in the mouth of a fish for its entire adult life? These isopods begin life as free-swimming males only a few millimetres large. Once it encounters a suitable fish host, it will settle, grow, and lose its ability to swim. If a female is already present on the host, the newly-arrived male will mate with the female and settle on the same host. If no female is present, or if the female eventually dies, the male has the ability to metamorphose into a female and await the arrival of another male.

A parasitic isopod *Cymothoa exigua* stays in the mouth of a juvenile tomato anemonefish *Amphiprion frenatus* after chewing away the tongue of the fish. **JL**

THE FREE RIDER

The slender remora (*Echeneis naucrates*) is sometimes seen swimming within and around the coral reefs of Singapore. Remoras are commonly known as 'sucker fishes' due to a sucker-like organ at the top of their bodies, located near the head. In reality, this organ is a highly modified first dorsal fin. The structure of the sucker bears little resemblance to a fin. Slat-like structures on each sucker can open and close, creating suction that allows it to hang on to larger marine organisms such as sharks and turtles. Other than obtaining a free ride, remoras have also been known to scavenge on the bits of food that fall as the host feeds. Some species, including the slender remora, have also been known to consume excreta from their hosts.

The remora *Echeneis naucrates* uses a sucker-like organ at the top of its body to stick to larger marine animals like turtles and sharks. **DT**

DEFENSE, OFFENSE: TO EAT AND AVOID BEING EATEN

How does one ensure a meal yet refrain from being another's supper? Reef organisms employ a wide arsenal to ensure that this fine balance is kept in place. In this section we take a closer look at some common strategies reef organisms use to outwit competitors in the evolutionary race on reefs.

OF BODY ARMOUR AND SPINES

Physical traits can aid in making some animals unpalatable. The hard outer skeleton of crabs and shrimps, known as exoskeleton, is a natural armour against predators.

The spiny lobster *Panulirus versicolor* has a tough exoskeleton and spines. By rubbing their long spiny antennae against their carapace, they can create loud screeches to deter their predators. **LN**

The fan-bellied leatherjacket *Monacanthus chinensis* at Pulau Hantu. **JL**

The skins of some fishes are modified and thus grant them some protection against predators. In addition to their rough skins, leatherjackets (Monacanthidae) also possess one rigid spine on the head to deter predators!

Seahorses (*Hippocampus* spp.) are slow-moving fishes, known for their unusual parenthood practices. Males of these species have brooding pouches into which females deposit eggs. Fertilised eggs develop in the brood pouches of the male seahorses. Eggs hatch into fully formed juvenile seahorses within the brood pouch before being released into the water. All seahorses have greatly reduced fins and lack a caudal fin. So how do these slow-moving seahorses protect themselves against the many roving predators in reefs? A series of ringed bony plates along the body of the fish covered by thin skin forms a 'skeletal armour'. In addition, the prehensile tails of seahorses allow them to hang on to various organisms on the seafloor such as soft corals, algae and seagrasses. Their slow movements and cryptic colouration also aid in allowing them to escape the notice of many a predator.

Spines on the head and bony plates on the body of the tiger tail seahorse *Hippocampus comes* help protect it from some predators. **MS**

Seahorses like this tiger tail seahorse *Hippocampus comes* can curl their tails to hang onto corals, sponges and seagrass. **JL**

Sea urchins such as *Diadema setosum* keep algae on the reefs in check. Their long sharp spines deter potential predators! **HD**

The needle-spined sea urchin, *Diadema setosum*, is a common sight on our reefs. These slow-moving organisms feed on algae using several small bony 'teeth' plates found on their underside, which is in contact with the substrate. *Diadema setosum* has numerous long hollow spines that deter any potential predators. These sharp fragile spines penetrate skin and flesh of persistent predators readily and break easily to leave portions embedded in the predator, causing much pain and discomfort.

TOXINS AND STINGS!

Sponges are sedentary animals without skeletons to keep them upright. Instead, they are held together, and upright, by a structural framework of many spicules made from silica or calcium carbonate. Although the spicules are mild irritants, they deter only few predators. The main deterrent are secondary metabolites that sponges produce, which are toxic to most organisms. Very few organisms are able to assimilate these toxins and the strategy offers good protection to sponges.

The spicules and toxins in the sponge *Xestospongia testudinaria* are poisonous for most organisms. **KYP**

Hydroids like *Macrorhynchia* sp. may look harmless but they are full of stinging cells. **KYP**

Members of the Hydrozoa, also commonly known as stinging hydroids, are ubiquitous in our reefs. These fern-like organisms are in fact colonial animals. They are closely related to corals and jellyfishes, and like their relatives, harbour stinging cells. These small predators use the stinging cells to capture passing zooplankton and other small invertebrates.

SHOOTING VENOM

Of over 2,000 species of venomous fishes, few are more feared than the reef stonefish (*Synanceia verrucosa*). Its highly cryptic colouration as well as extremely low swimming activity provides the fish with an apt common name. Camouflaging very successfully amongst rubble and other coral organisms, this fish ambushes unsuspecting small fishes and invertebrates that are passing by. Stonefishes produce neurotoxins and store them in venom sacs at the base of their dorsal fins. The spines of the dorsal fins are hollow, similar to hypodermic needles. If stung, immediate medical attention is advised as the venom causes extreme pain, and in some cases, can be fatal.

The stonefish *Synanceia horrida* is an expert ambush predator on Singapore's reefs and its spines contain powerful venom. **NML**

BEAUTY AND BRAIN

Nudibranchs are unlike other molluscs such as clams and snails in that they are soft-bodied and do not possess hard shells. Most are brightly coloured despite moving slowly. The attractive colouration serves as a warning to potential predators of their toxicity and unpalatability. Yet, these creatures do not manufacture their own toxins. Instead, the toxins are ingested from organisms such as sponges, corals and tunicates, and then incorporated into their own tissues. Nudibranchs are thus able to afford protection without investing significant resources required to produce their own toxins.

Nudibranchs like *Doriprismatica atromarginata* are one of the most charismatic animals. Their vibrant colours serve as a warning to predators. **ARR**

A nudibranch *Cuthona yamasui* feeding at Sisters' Islands. **JL**

A pair of nudibranchs *Bornella anguilla* on hydroids at Pulau Tekukor. **JL**

Small but deadly

Small marine snails, perceived as slow-moving, can be one of the most vicious predators when in large aggregations. Pyramid snails (*Turbonilla cummingi*, about 6 mm length) are inconspicuous predators of the giant clam. These snails shelter in pits and grooves on the clam shell during the day and feed on the mantle, by sucking its fluids at night. While only one snail may not hurt the clam, hundreds of them can lead to the death of the giant clam. **LY**

Pyramid snails *Turbonilla cummingi* hiding during the day, under the byssal orifice of the giant clam. **LY**

Armed with a specialised radula supporting long lateral teeth, *Drupella* snails feed by scraping live tissue off corals. Two species occur in Singapore — *D. rugosa* and *D. margariticola*. These corallivores are nocturnal, small in size (up to 5 cm length) and highly cryptic. Outbreaks of *Drupella* snail populations can deplete up to 35 m^2 of coral reef, about the area of three car parking lots, in two months, thus generating coral rubble fields that will consequently be dominated by algae. **SSQ**

Drupella snails feeding on live tissues of *Platygyra* coral, exposing the coral skeleton. Lazarus east, Singapore. **SSQ**

Drupella snails feeding on live tissues of *Favites* coral, exposing the coral skeleton. Lazarus west, Singapore. **SSQ**

THE NON-SEEING EYE

Several species of butterflyfishes from the family Chaetodontidae are common in our reefs. These fishes are specialist predators, feeding on coral polyps or small invertebrates found in between crevices of the reef. Despite their bright and attractive colours, these fishes are not known to harbour toxins or venom. They are thought to avoid predators by several means. Butterflyfishes have laterally flattened bodies and are shaped like a disc. Thus, even though they are brightly coloured and broad when viewed from the sides, they are hardly noticeable when viewed from above or below. In addition, many species of butterflyfishes have an ‘eye spot’ or ocellus near the tail. It is thought that predators perceive the fish as larger than they truly are due to the large eye spot. That the eye spot is usually found on the rear end of the body have led scientists to hypothesise that predators might mistake the tail end to be the head and approach it from the perceived head end in full view of the butterflyfish, allowing for early detection and escape. There might be some merit to this theory as the real eyes of butterflyfishes are often masked within coloured bands.

The fake 'eye' near the tail of the copper-banded butterflyfish *Chelmon rostratus* tricks predators into believing that the tail is the head of the fish. **JL**

SAME BUT DIFFERENT

Many theories have been suggested as to why fishes move around in schools. Schooling is truly a behaviour that has different functions for different species. In species such as damselfishes (Pomacentridae) and fusiliers (Caesionidae), schooling allows earlier predator detection and decreased chances of being targeted as a prey, while in species such as barracudas (Sphyraenidae), schooling allows for more effective hunting of prey species. When predator species such as barracudas cooperate in hunting, the success rates are higher as they can either shoal species before attacking, or break up schools and prey on disorientated individuals.

Schooling fish can detect predators easily and face reduced chances of being eaten. **SSQ**

Fishy juvenile fishes

Fishes are vulnerable during their early life stages due to competition and predation. The behaviour of juveniles of many fish species can help increase survivorship. **DT**

A juvenile false clown anemonefish *Amphiprion ocellaris* (3 cm length) found at Sultan Shoal, inhabits a magnificent sea anemone *Heteractis magnifica*. The juveniles associate with host sea anemones and continue to spend their entire lives between the venomous tentacles of the host, safe from predators. **DT**

This juvenile eight-banded butterflyfish *Chaetodon octofasciatus* (2 cm length) shelters among branches of *Acropora loripes* in the underwater coral nursery off Seringat Island and feeds on the coral polyps. **DT**

A juvenile of the many-spotted sweetlips *Plectorhinchus chaetodonoides* (5 cm length) observed in the underwater coral nursery off Seringat Island, perfectly mimicking the undulating movement of a flatworm. **DT**

This laterally compressed juvenile razorfish *Aeoliscus strigatus* (1 cm length) was photographed at Sultan Shoal. Juveniles can be easily mistaken for a floating blade of seagrass due to their shape and swimming pattern. They hide from predators between the spines of *Diadema* urchins. **DT**

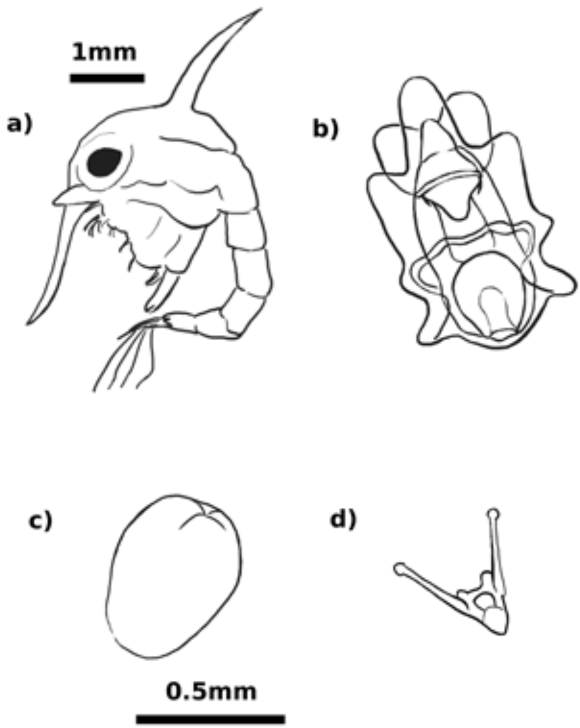
MAKING CONNECTIONS

The term 'connectivity' is commonly used in ecology. In the marine environment, seawater is an effective medium for transporting materials, light or heavy, from place to place. Nutrients can be carried along and distributed in the same way as pollutants. Larvae can also be dispersed by currents so that those produced from a reef (referred to as a ‘source’ reef) will end up settling on another reef (referred to as ‘sink’ reef) downstream of the current.

Planktonic larval dispersal

Imagine a world with an infinite number of roads or highways. This is the sea. There are many small ‘tunnel roads’ created by coral reef structures. There are also major ‘highways’ such as the ocean conveyor belt currents that traverse the Earth’s oceans. Larvae of marine organisms are easily moved by water currents. Although most larvae have limited mobility, some are able to control to a certain extent, the distance and direction of travel by adjusting their vertical position within the water column. Some larval organisms can travel thousands of kilometres, while others remain within a few metres of their parents. Regardless of the dispersal distance, transported larvae will perish unless they are able to find a suitable habitat to settle in before they mature. This is a specific duration, known as the settlement window, when the larvae are capable of attaching to a suitable substrate and undergo metamorphosis. They continue with their life cycle at this location, until they reach reproductive maturity. Transfers and/or exchanges of larval organisms between one coral reef area and another, as well as among habitats, contribute to replenishing diversity pools of reproductive individuals, and maintaining genetic vigour. Successful transfers to new localities may sometimes found new populations. **TYC**

Examples of some larval forms of four invertebrate species encountered in Singapore.
(a) crab zoea,
(b) sea star bipinnaria,
(c) coral planula, and
(d) sea urchin pluteus.
Scale bar for all but the crab zoea represent 0.5 mm. **TYC**



Coral reefs, seagrass meadows and mangroves are highly productive coastal and marine habitats that are rich with biodiversity. Where they occur next to each other, they appear to 'enrich' each other. For example, small pieces of seagrass leaf blades break off and are carried by currents to adjacent mangroves or coral reefs, which can assimilate this additional nutrient input. Similarly, nutrients from mangroves and coral reefs also get transported between them. Various species also move between habitats and benefit from the best that each offers in terms of food and shelter. Yet other species spend different stages of their life history in different habitats.

Connectivity allows species to optimise the biological productivity, food and sanctuary that each habitat offers. A coral reef that is close to a seagrass meadow and a mangrove area benefits from the exchange of biological materials. It is also said that coral reefs next to a seagrass habitat show a lower incidence of coral disease. This is because seagrasses release bioactive compounds that are carried over to adjacent coral reefs and prevent corals from getting diseases.

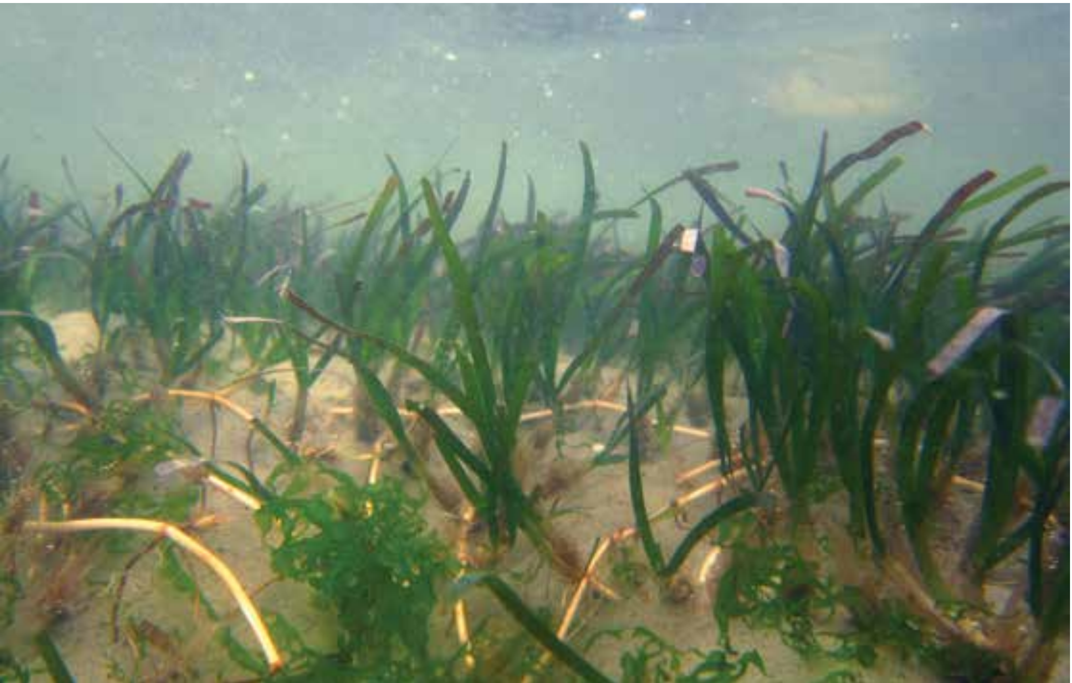
Large patches of sea anemone can be found on Singapore's reefs. **DT**

Coral reefs – seagrass beds connectivity

Seagrasses are marine flowering plants that grow in shallow coastal waters. These plants sometimes form meadows with high connectivity to adjacent coral reefs. Snappers, goatfishes, and rabbitfishes utilise both seagrass and reef habitats. Uprooted or decaying seagrasses are sometimes consumed by sea cucumbers, corals, sea anemones, and ascidians when transported by water currents to neighbouring reefs.

Water that flows through seagrass beds before reaching coral reefs have lower levels of sediments, land-based nutrients and pathogens. Consequently, disease levels in coral reefs adjacent to seagrass meadows are lower compared to those that are not. Besides removing large amounts of carbon from seawater, productive meadows can also raise seawater pH and aragonite saturation state, which potentially enhances coral growth. Seagrass meadows may thus enhance coral reef resilience to climate change and ocean acidification. **OYX**

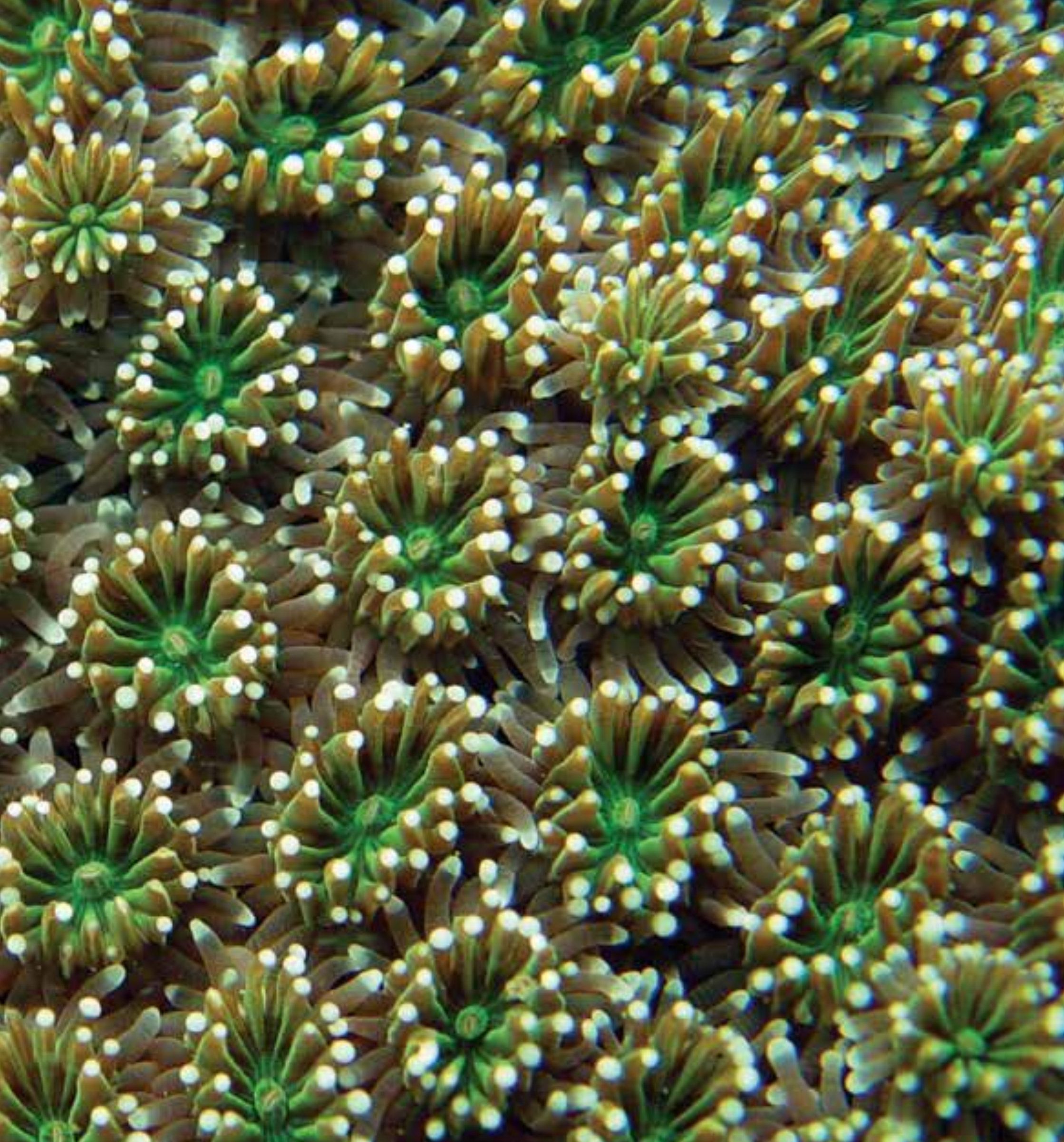
Meadow with tape seagrass *Enhalus acoroides*, with coral in foreground and oil refinery in the background. Pulau Hantu. **OYX**



Smooth ribbon seagrass *Cymodocea rotundata* with exposed rhizomes at Chek Jawa. **OYX**

Sickle seagrass *Thalassia hemprichii* with female flowers at Labrador beach. **RT**

4 TEMASEKIA



Singapore's coral reefs support a multitude of interesting flora and fauna, such as the galaxy coral *Galaxea fascicularis*. **CLM**

Singapore's coral reef habitat is filled with immense biodiversity and even the smallest reef patch supports an interesting assemblage of species. These species have been around even before the founding of the island named Temasek. Most species also occur in the coral reefs of neighbouring countries as marine life is easily distributed by currents.

There are possibly a few species that are confined to Singapore but studies have not been extensive. The Comprehensive Marine Biodiversity Survey uncovered new species, as well as many thought to have become locally extinct. Whether they are found only in Singapore, or have a wider regional distribution, they form a natural heritage that belongs to the country.

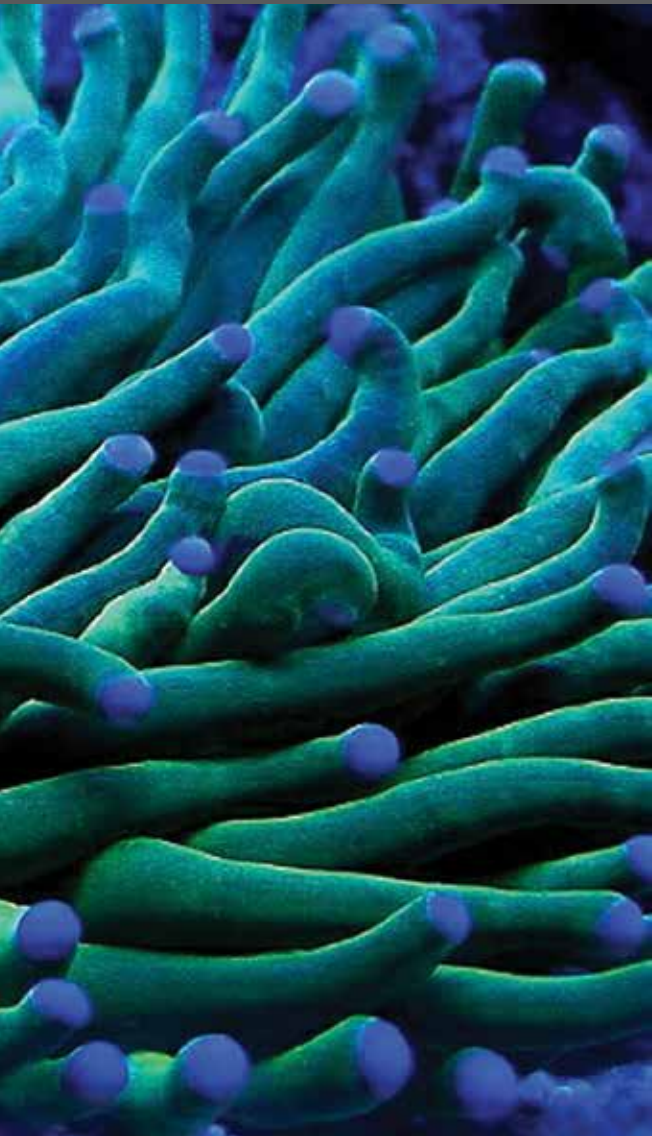
There is no single basis for the species featured here. Some are more commonly encountered on our reefs than others. Some are more recent discoveries. What they all share are fascinating aspects of their lives that contribute to the total vibrancy of Singapore's coral reef habitat.

The coral reef is an important habitat type for a wide diversity of organisms. **DT**

Heliofungia actiniformis

This circular-shaped, solitary mushroom coral is easily distinguished by its fleshy elongate tentacles with cream-coloured tips, which remain extended throughout the day. At first glance, they are easily mistaken as sea anemones. All other solitary mushroom corals have their tentacles retracted during the day, extending them only at night. Each colony is a single individual, lying unattached on the reef floor. They are found in the shallow reef zone. Adult individuals seldom exceed 13 cm in diameter. **CLM & KT**

The mushroom coral *Heliofungia actiniformis* has its tentacles fully extended during the day, resembling sea anemones. **CLM**



Like many other species of stony corals, *Heliofungia actiniformis* exhibits striking fluorescent colours under ultra-violet light. **KT**

Galaxea fascicularis

The galaxy coral has polyps that each resembles a star burst. It is highly sought after in the aquarium trade. However, the coral skeleton is very brittle and they do not fare well in captivity. Most of the tentacles have distinct white tips that can be induced to form specialised sweeper tentacles extending up to 30 cm. These sweeper tentacles are very aggressive and can damage and kill adjacent corals. **TTC**

Galaxea fascicularis are colonial animals that form columns. **LN**

The polyps of the galaxy coral *Galaxea fascicularis* resemble star bursts. **CLM**

Rhodactis indosinensis

When the tide recedes, not many animals are as inconspicuous as this ubiquitous corallimorph, which forms slimy blobs when emerged. But when submerged, these sea anemone-like creatures spread open their oral discs, exposing the upturned mouths, tentacles and intricately-textured discs that can have very distinct and beautiful forms. Commonly but awkwardly known as the 'hairy mushroom', it is not hard coral, soft coral or sea anemone. Corallimorphs have been dubbed 'naked' corals for their close affinities to stony corals. **ORM**

The 'hairy mushroom' corallimorph *Rhodactis indosinensis* forms slimy blobs when emerged from water, sometimes resembling carpet anemones. **ORM**

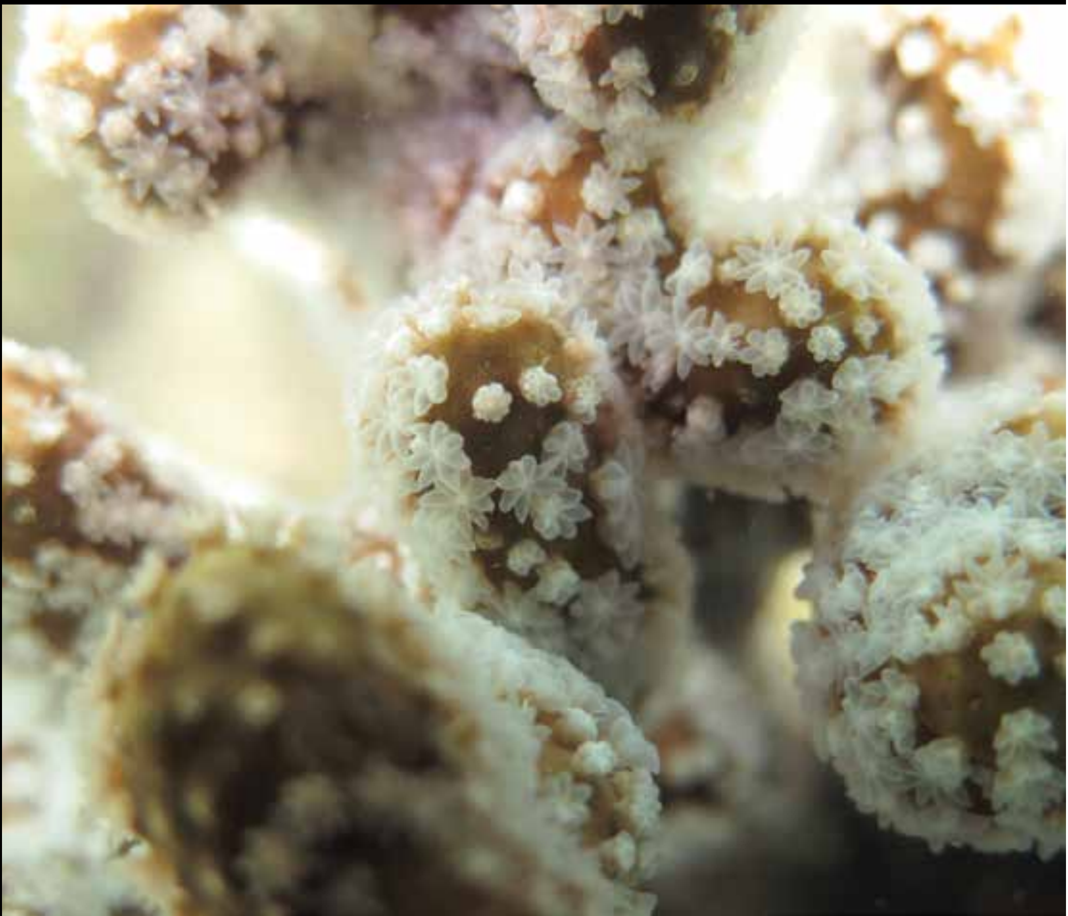
The 'hairy mushroom' corallimorph *Rhodactis indosinensis* with simple to branched tentacles extended when submerged in water. It resembles sea anemones but has a protruded mouth. **NML**

Heliopora coerulea

The blue coral is closely related to soft corals but they produce a hard aragonite skeleton. On the surface, they appear brown but their internal skeleton is blue, due to deposits of iron salts. In April every year, female blue corals in Singapore brood, forming a dense white mat on their surfaces. By holding on to their developing larvae with their extended tentacles, they minimise the duration of the larvae floating free in the water and increases their chance of survival. **TTC**

The internal skeleton of *Heliopora coerulea* is blue. **KYP**

The external surfaces of blue corals are brown, but during the annual mass brooding event, dense white mats can be observed. **TTC**



Blue corals *Heliopora coerulea* fertilise the eggs internally and brood larvae on their surfaces. **TTC**

Spongia ceylonensis

Natural sponges function better than the man-made ones that we use today. Older generations of Singaporeans knew of the existence of bath sponge species in our coral reefs, yet this interesting fact is not known by many younger Singaporeans. Ironically, inhabitants of the Mediterranean coast have been using bath sponges for over 3,000 years but no bath sponge species have ever been recorded from that region! **LSC**

The bath sponge *Spongia ceylonensis* can be found on intertidal zones of Singapore's shores. **LSC**

Bath sponges *Spongia* spp., as the one above, are still sold as commercial products in Singapore. **LSC**

Sabellastarte spectabilis

This fanworm offers quite a sight as its feather-like crown flutters amidst coral colonies. The crown is important for respiration and as a food receptacle. The remainder of the worm is contained in a self-built mucus tube attached to hard surfaces like coral skeletons. Tiny hooks along both sides of its body help it to hold on to the tube. It can retract itself entirely into the tube when the tide is low or when it senses harm. This species begins life as a male and can change sex to female later in life. It also has the ability to regenerate damaged segments. **LYL**

The fanworm *Sabellastarte spectabilis* has a feather-like crown that allows it to respire and capture prey. **LYL**

Doridomorpha gardineri

This oval-shaped nudibranch species lives, feeds, and lays eggs specifically on their host, the blue coral *Heliopora coerulea*. The combination of a tiny size and perfect camouflage makes it a difficult species to spot. Individuals grow to approximately 1 cm and usually appear brownish. Throughout its body are sparse white and brown speckles that closely mimic the host's polyps, and they are easily mistaken as flatworms. Their eggs, laid in a spiral ribbon, hatch within just five days! **LYL & RO**

This nudibranch *Doridomorpha gardineri* is found exclusively on blue coral and is well camouflaged on the host's surface. **RO**

Doto greenamyeri

The donut *Doto* is a nudibranch with characteristic rounded discs on its body. These discs, resembling donuts, hence the common name, are false gills known as pseudobranchs. The donut *Doto* was discovered in Singapore only in June 2014 during the Comprehensive Marine Biodiversity Survey. Since then, it has been observed often by recreational divers at Pulau Hantu. **ZJ**

The donut nudibranch *Doto greenamyeri* at Pulau Hantu. **DM**

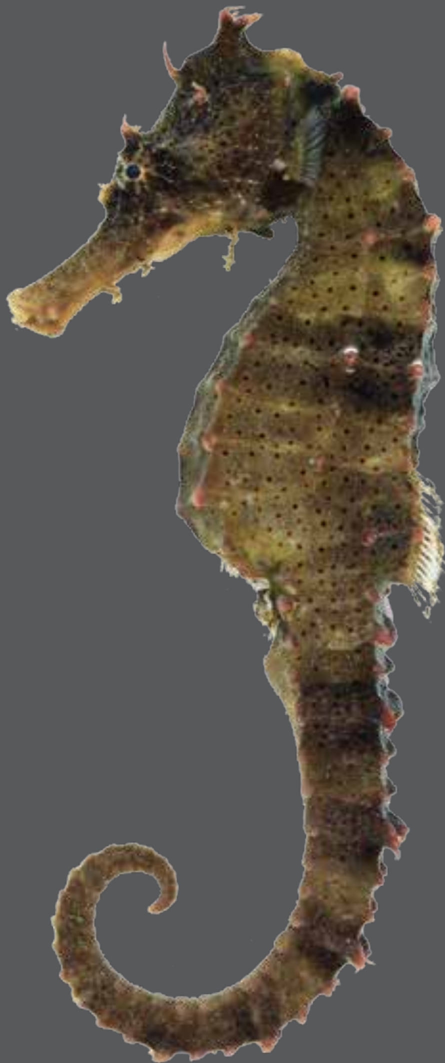
Phanogenia typica

When touched, the sticky crinoid feels extremely adhesive due to the densely-packed spines on its pinnules, which are secondary branches of its arms. Unlike most crinoid species, which typically possess specialised appendages called cirri for attaching to substrates, adults of this species lack them but instead rely on the strong adhesiveness of the pinnules. It is not encouraged to touch these animals as their arms tend to detach easily, more so than other species. In Singapore, this species can be found at depths up to 18 m and is often cryptic in nature, half hidden in crevices or under corals. **LYL**

The arms of the sticky crinoid *Phanogenia typica* may look strong but they are actually very brittle. **LYL**

Hippocampus kuda

The spotted seahorse is the original Temasekian. Although distributed throughout the Indo-Pacific, this species was first described from Singapore in 1852. Pieter Bleeker, a well-known ichthyologist, called this species 'kuda', Malay for horse. This species is uncommon in the reefs of Singapore, and is considered vulnerable to threats throughout its range. **ZJ**



The spotted seahorse, *Hippocampus kuda*. **RO**

Ostorhinchus margaritophorus

The red-striped cardinalfish must be the model for Singapore's 'Dads for Life' campaign as the males are the ones brooding eggs in their mouths. This mouth-brooding behaviour is also reported in males of many other species of cardinalfishes. During periods of mouth brooding, lasting approximately a week, these males do not even feed! This stunning photograph from Heng Pei Yan won the Singapore Garden Photographer of the Year 2017. **ZJ**

A mouth-brooding male red-striped cardinalfish *Ostorhinchus margaritophorus*. **HPY**

Doryrhampus janssi

The bright orange and blue Janss' pipefish was discovered to occur in Singapore only on 29th October 2005 by Zeehan Jaafar and Jani Tanzil, who were surveying the coral reefs of Pulau Jong for fishes associated with invertebrates such as soft corals. Swimming back to the boat once work was completed, Zeehan chanced upon three individuals of the Janss' pipefish. Jani then took the first photo of these fishes in Singapore. Together with Jeffrey Low, they shared this new finding with the community. This elegant pipefish has since been observed on coral reefs off other southern islands of Singapore. **ZJ**

Janss' pipefish *Doryrhampus janssi* studied during the Comprehensive Marine Biodiversity Survey in 2014. **RO**

The first Singapore record of Janss' pipefish *Doryrhampus janssi* at Pulau Jong. **JT**

5 FUTURE OF OUR REEFS

Sisters' Islands at low tide. **HPY**

OF WHAT USE ARE CORAL REEFS?

PRODUCTIVITY

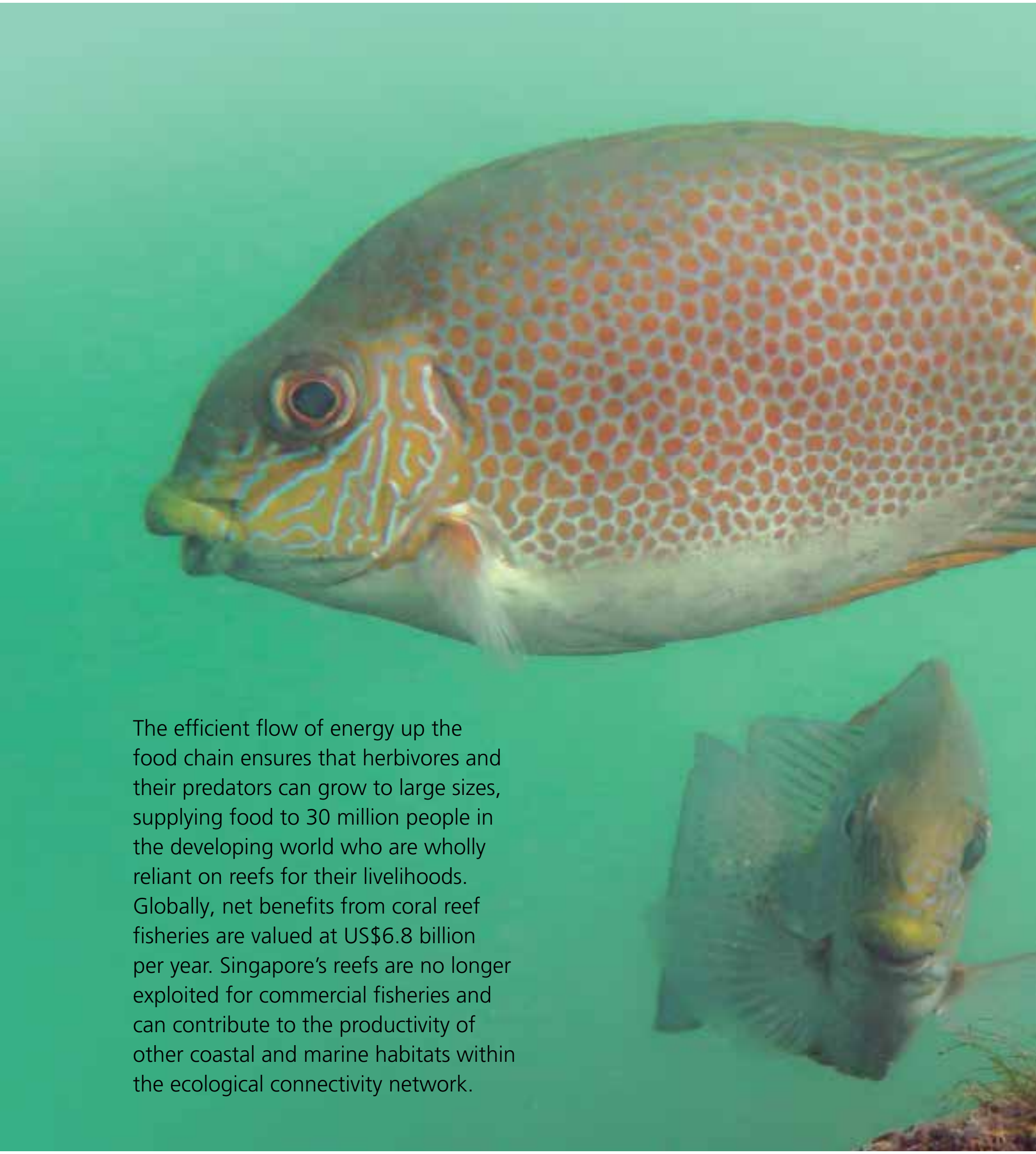
Singapore's coral reefs provide an abundance of food, adequate space for species interactions, and support a unique diversity of reef organisms. At first glance, the coral reef habitat appears different from other biological habitats by having more consumers than producers. Plants, the primary producers capable of harnessing sunlight energy to convert carbon dioxide and water into food and oxygen, form the base of the food pyramid, and are always more abundant than consumers, which feed on plants and on one another. Hence the biomass of consumers becomes smaller with each level up the food pyramid, explaining why top predators are few in numbers.

In forests and mangroves for example, plants dominate. This is not the case in coral reefs in which you see more consumers than producers. Corals, which form the dominant group, are animals — and are thus consumers. Plants and algae, organisms that photosynthesise, are never as abundant as the consumers on a reef. This inverted food pyramid is ecologically novel due to an innovative evolutionary breakthrough. In coral reefs, the producer lives within the consumer and is the reason why coral reef habitats are highly productive.

Zooxanthellae packed inside the cells of corals result in an efficient producer-consumer relationship because almost nothing is lost to the environment. Wastes of one partner become nutrients for the other and the close proximity makes recycling efficiency optimal with minimal leakage into the environment. This explains why reefs can occur in nutrient-poor environments exemplified by the clear tropical waters that house the most pristine reefs. The zooxanthellae-coral relationship model is also observed in other reef animals like giant clams and some marine slugs that also habour zooxanthellae.

Coral reefs develop well in clear waters with low nutrients. **HD**

Coral reefs generate among the highest production per unit area on Earth, rivalling the most productive plant ecosystems on land. Despite this, there is little spillage of nutrients out of the reef community. Nutrients flowing through zooxanthellae directly nourish corals that build the magnificent limestone structures. Other producers include small encrusting, filamentous or fleshy algae that are quickly grazed by herbivores.



The efficient flow of energy up the food chain ensures that herbivores and their predators can grow to large sizes, supplying food to 30 million people in the developing world who are wholly reliant on reefs for their livelihoods. Globally, net benefits from coral reef fisheries are valued at US$6.8 billion per year. Singapore's reefs are no longer exploited for commercial fisheries and can contribute to the productivity of other coastal and marine habitats within the ecological connectivity network.

Reef fishes such as the golden rabbitfish *Siganus guttatus* (two at left) and masked bannerfish *Heniochus monoceros* (right) are of high commercial value. **DT**

Reef fishes also migrate to adjacent mangroves and seagrass beds that serve as nurseries for their young. The juveniles may become food for predators in those habitats, effectively exporting production from reefs to adjacent environments.

Herbivores such as the Java rabbitfish *Siganus javus* help to prevent excessive build-up of algae on the reef. **DT**

SHORE NOURISHMENT AND PROTECTION

Coral reefs exist as the net result of the processes of reef building and erosion. Growth of reefs occurs due to secretion of calcium carbonate by corals but is also opposed by erosional processes. These can be biological in nature, such as boring by bivalves and scrapping by parrotfishes, or physical, due to strong wave action. Material eroded from reefs are deposited on the shore and help build beaches with white sand.

This giant clam *Tridacna crocea* bores into coral, eroding the reef's calcium carbonate framework. **HD**

Pulau Hantu: Singapore's island getaway

The coral reefs around Pulau Hantu are one of the most popular areas for leisure scuba diving activities in Singapore. These reefs, and those of the nearby islands, are known for the high diversity of small organisms that live in symbioses with host organisms. The occasional encounter with sea snakes, sea turtles and reef sharks serves as a bonus to divers. Although recreational fishing is also popular at these sites, there also exists a growing ground-up initiative to release catches to conserve fish resources and minimise impacts to the coral reefs.

Diver during a surface interval at Pulau Hantu. **DN**

Intertidal walk during low tide at the lagoon separating Pulau Hantu Besar and Pulau Hantu Kechil. **DN**

The outreach efforts of marine volunteer groups such as Hantu Blog, Blue Water Volunteers, Wild Singapore and the Naked Hermit Crabs, have successfully showcased the uniqueness of local reefs, and the conservation efforts required to protect them. **DN**

Singapore is relatively sheltered from extreme weather and coastal events such as tropical cyclones and tsunamis because of its location. However, storms and fast currents in the Singapore Strait can induce strong waves that batter the coast. Coral reefs form natural barriers that dissipate the high wave energy, hence are instrumental in decreasing instances of shoreline erosion and storm damage. Globally, reefs protect about 150,000 km of shoreline, equivalent to about US$10.7 billion of annual net benefit. Many low-lying islands in oceans would also not have existed if not for the physical protection afforded by reefs.

Corals form natural barriers that protect our coasts. **TTC**

Useful drugs from bacteria?

Marine cyanobacteria are sometimes mistaken as algae but they are actually photosynthetic blue-green bacteria. These microorganisms obtain their energy through photosynthesis and occur in various marine environments, such as coral reefs and intertidal habitats. Cyanobacteria have an extensive fossil record, dating back to more than three billion years, and are responsible for giving Earth all of its oxygen. They play an essential role in coral reef ecosystems by forming microbial mats and are found associated with benthic marine invertebrates, including sponges and tunicates. Certain marine cyanobacterial strains, such as *Trichodesmium* and *Lyngbya* species, can form extensive blooms when environmental conditions are conducive. These bloom-forming cyanobacteria can severely impact aquatic ecosystems and human health due to their production of (cyanotoxins) such as lyngbyatoxins and aplysiatoxins. These cyanotoxins can cause inflammation of the skin (dermatitis) and induce tumour formation. On the other hand, certain filamentous marine cyanobacterial strains, such as *Moorea producens* and *Symploca* species, are known to produce useful bioactive compounds with biomedical potentials. For instance dolastatins 10 and 15 are small organic linear peptide molecules, found to be promising drugs for the treatment of breast and liver cancers. In fact, a synthetic version of dolastatin 10, known as monomethylauristatin E, is currently used to treat patients with blood cancers, such as Hodgkin's lymphoma. **TLT**

Cyanobacteria such as *Lyngbya* sp. produce toxins that can cause severe skin inflammation. **TLT**

IS THERE A PROBLEM WHEN IT IS NOT SEEN?

Despite the ecological and economic importance of coral reefs, the general population remains unaware of even the existence of Singapore's reefs. The habitat is not conveniently accessed and cannot be seen at leisure to be generally appreciated. With the loss of mainland reefs, visitors have to boat across to the southern offshore islands but get to see little without snorkeling or scuba diving. Intertidal reef flat walks are possible at low spring tides that occur fortnightly but commonly at the inconvenient times of early dawn or late evening. The turbid water has also made it impossible to see the reef from a boat (this was possible in the 1960s). The reefs have moved out-of-sight and suffer the out-of-mind consequence. They remain obscure to most of the modern generation.

Turbid water is a common sight in Singapore. **TTC**

Corals and fish are widely used in the aquarium trade. **DW**

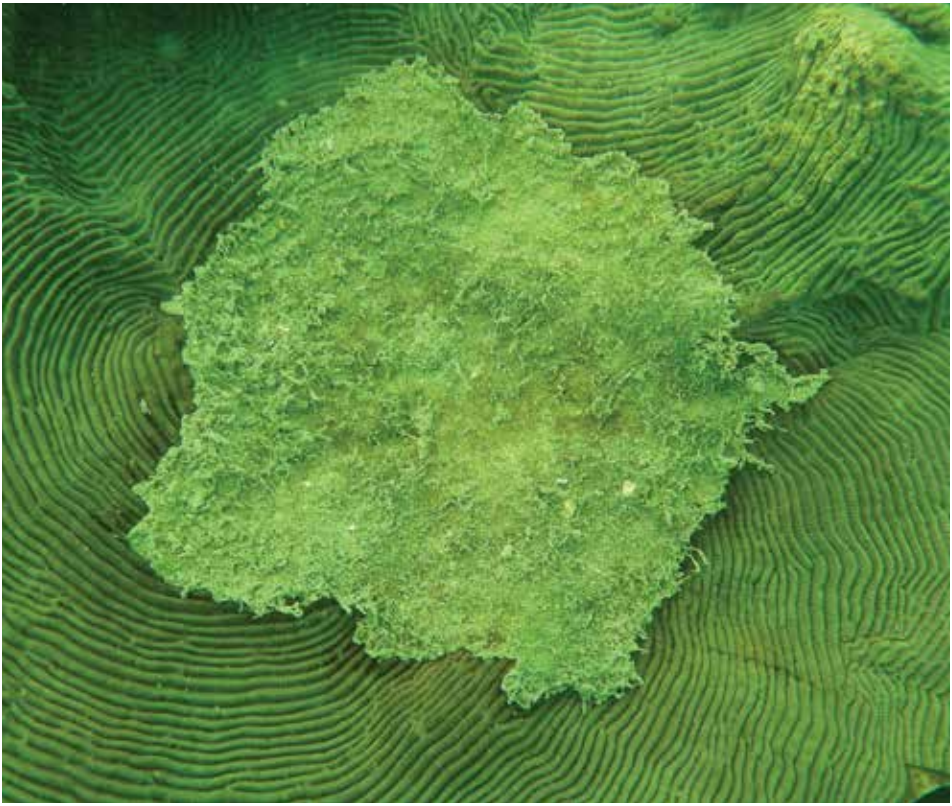
Past generations of coastal communities have relied on the reefs for sustenance. Many in the small village settlements of Pulau Sudong, Pulau Semakau and Pulau Sakeng lived mostly off the reefs for food and to a smaller extent, income supplement from the sale of reef ornaments. Harvesting at subsistence levels allowed the reefs to provide until 1977 when most of the Sudong and Semakau residents were re-settled on the mainland. None of the southern islands remained inhabited after the final 150 residents of Pulau Sakeng were resettled in 1994. However, increased pressure on the reefs came from the flourishing marine aquarium trade that grew rapidly in the 1970s, aided by the absence of effective regulatory mechanisms to prevent excessive harvesting and its resultant damage. The exploitation included harvesting of colourful reef creatures as well as entire coral colonies for export. This was a time when the reefs suffered greatly from the tragedy of the commons. Coral reefs were open-access resources greedily exploited by almost anyone out to make easy cash.

WINNING ECONOMY, LOSING REEFS

Coastal development and land reclamation went on overdrive in the 1970s, a bleak period for Singapore's coral reefs. The habitat was mostly viewed by decision makers as having a nuisance value because of the threat to safe navigation. There was even a little-known proposal that valued the reefs in terms of the amount of cement they can generate. It appeared to be a perfect solution – remove the reefs for safer shipping and turn the coral organisms into cement, which was in high demand fuelled by the country's construction boom. It was an ideal economic win-win proposal, but did not take into account the ecosystem services that coral reefs provide.

The need for more land and port infrastructure increased dramatically as the economy grew and population expanded over the years. Well over 100 km^2 have been added to Singapore's land area, a 20% increase over its original size. By 2030, an additional 100 km^2 of land is expected to be reclaimed. Thus far, more than 60% of total reef area has already been lost to land reclamation and coastal modification. All the fringing reefs on the main island have been obliterated save for a tiny patch at Labrador beach. Even then, this small coral patch at Labrador faces a grim future due to impacts from adjacent coastal changes and development activities past and present.

The accumulation of sediment in Singapore's waters has reduced underwater visibility. **HD**



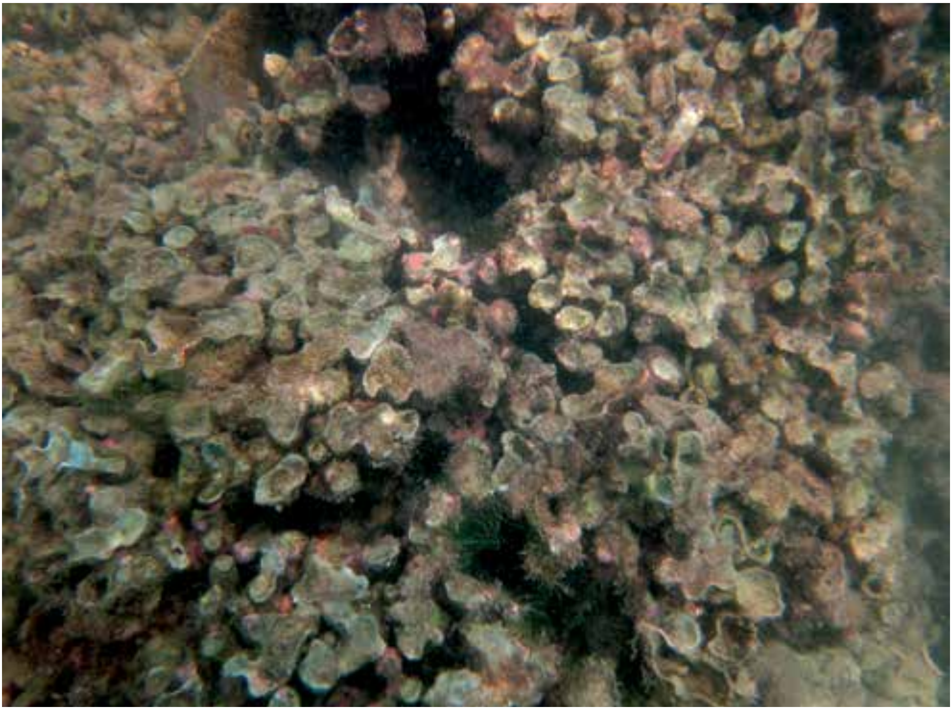
The tissues of the coral *Pachyseris speciosa* were killed when sediments smothered the coral's surface. **HD**

Decades of reclamation activities when tonnes of sand were dumped into the sea resulted in increased rates of sedimentation. Dredging of the seafloor occurs regularly to maintain the depth of shipping lanes. The remaining coral reefs have to endure a drastic decline in water quality as increasing turbidity decreased visibility from 10 m before the 1970s to a mere metre today. Just as humans are concerned with breathing increased air particles during periods of haze generated by forest burning, corals become stressed by excessive fine sediment particles in the water, which interfere with the coral's feeding, abrade their soft tissue, increase their energy demand to prevent smothering and reduce the all-important sunlight reaching them through the water. In response, corals no longer grow at depths beyond eight metres. In clearer waters of the past, corals grew healthily at 10-metre depth.

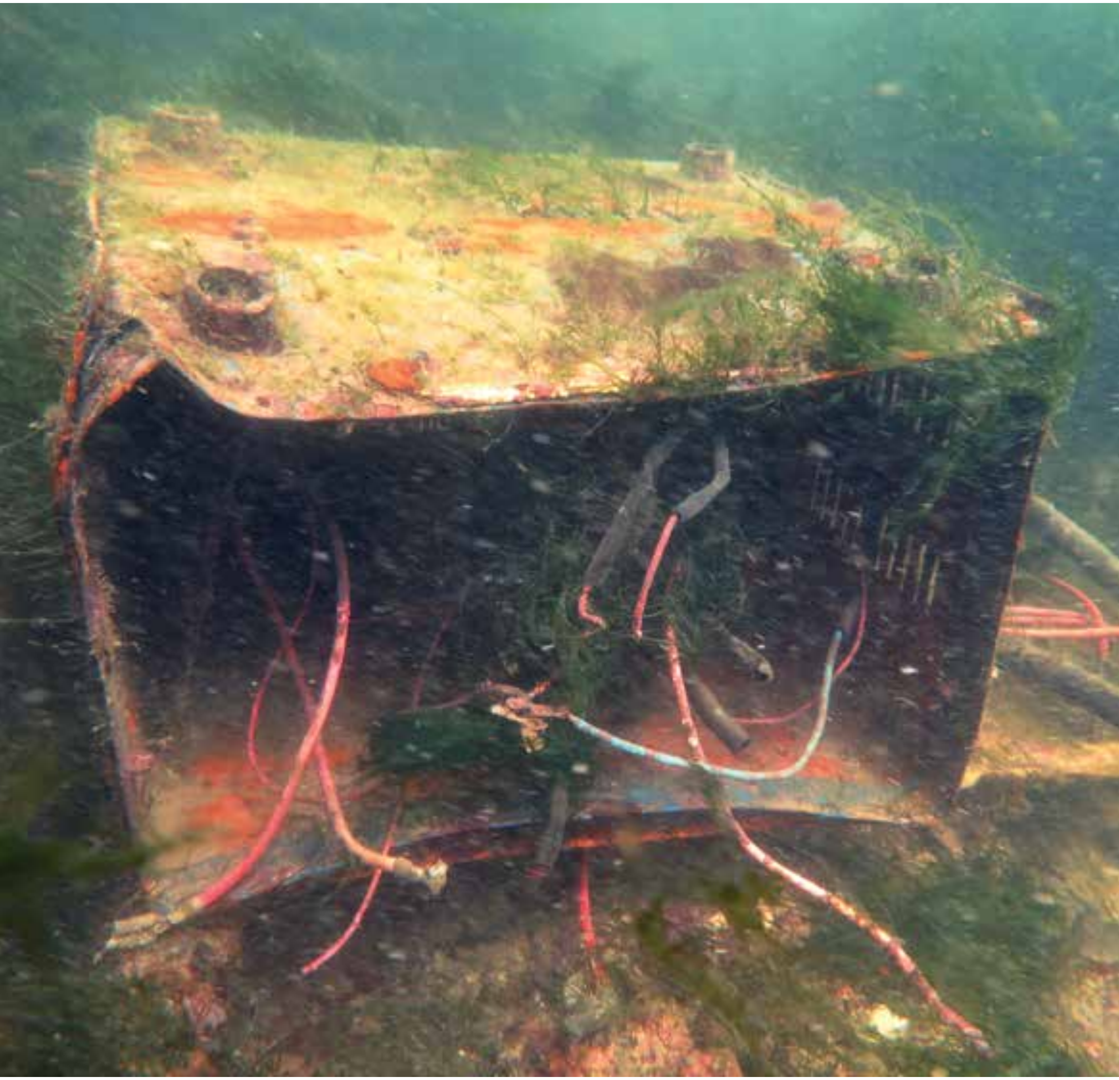
Meanwhile, the expansion of port facilities continues to encroach into the living reef at Labrador beach. In 2006, when the Pasir Panjang Container Terminal was to be expanded, pre-existing submarine cables servicing Pulau Bukom were in the way, and had to be relocated to the adjacent Labrador beach, potentially obliterating the western section of the reef. Offshore, the story is eerily similar. During the same year, Terumbu Bayan, a magnificent patch reef north of Pulau Hantu, had to be reclaimed for the building of a new petrochemical plant.

Part of Labrador beach was developed to expand the port facilities at Pasir Panjang. **HD**

More acute stresses to reefs also occur with much less warning. As one of the largest ports of call in the world, Singapore has extremely busy shipping traffic amongst its offshore islands and reefs. Not surprisingly, vessels have run aground on healthy reefs, and anchors dropped from small boats and dragged through tracts of coral colonies caused significant damage. Once corals are dislodged, there is high likelihood that they tumble down the reef slope and are unlikely to survive due to insufficient light and excessive sediment load.



Coral colonies damaged by vessel grounding at Kusu Island in 2014. **TTC**



Discarded equipment from a boat at the reef off Sisters' Islands in 2017. **TTC**

Serious shipping accidents can result in oil spills. The more severe in recent decades involved a collision between an oil tanker and a cargo ship in May 2010, releasing more than 2,000 tonnes of crude oil off the east coast of Singapore. Slicks reached the mainland and some of the offshore islands, but because of the long distance and quick containment by the oil spill response operations, reefs were not gravely stressed.

Oil spills smother the shores and cover the sea surface with chemicals. **HD**

Naturally, organisms living within coral reefs are susceptible to harsh weather conditions. Singapore experiences relatively calm weather, protected by islands of the neighbouring countries all around and are sheltered from extreme conditions such as tropical cyclones and tsunamis. However, Singapore's climate is influenced by two seasonal monsoons that can affect reefs. The Northeast Monsoon occurs between December and March and the Southwest Monsoon between May and September.

More extreme weather events generate stronger waves that can damage coral reefs. **HD**

Corals broken and dislodged from the reef rarely survive. **JL**

Heavy winds during the monsoon periods result in strong waves that can affect coral colonies growing in the shallow reef zones. Coral colonies with massive and submassive growth forms such as *Diploastrea heliopora* are less likely to be affected by these strong waves. However, those with foliose, branching and tabular growth forms such as *Montipora* and *Acropora* can be easily dislodged or damaged during these occasions. Solitary and free-living varieties such as the mushroom corals *Fungia* and *Heliofungia* have higher chances of being overturned and swept about by strong waves.

Free-living *Fungia* corals are easily overturned by strong waves. **DHI**

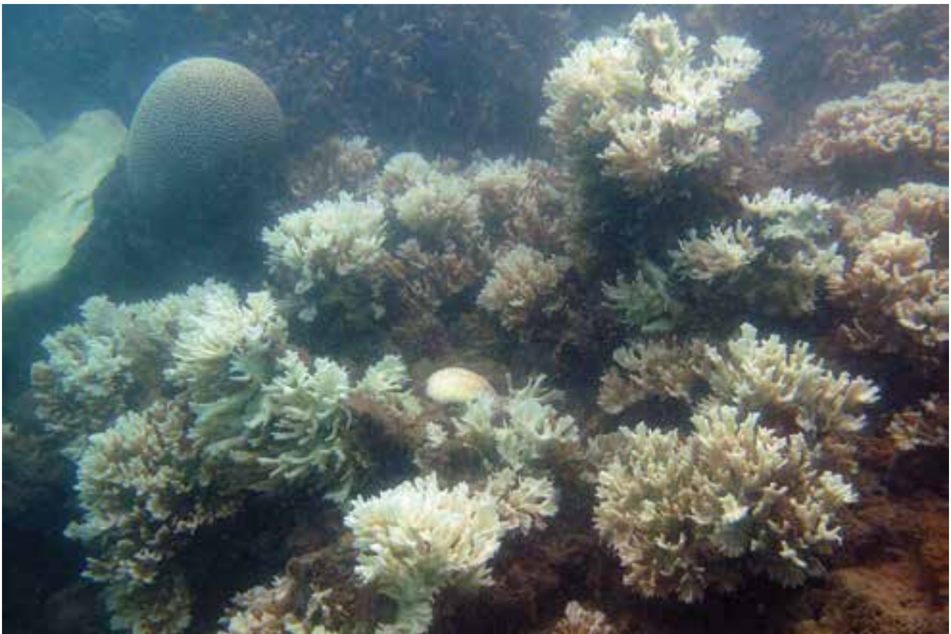
Surface runoff after a storm makes the water more turbid. **TTC**

Strong rain and storms can also affect reefs through terrestrial runoff. With an average rainfall of approximate 2,300 mm annually, terrestrial runoff contributes significantly to the conditions of our reefs. Sediments and nutrients washed from land into the sea during rainstorms cause decreased visibility. Lower light penetration can affect coral productivity and larvae of reef organisms. The chances of larval organisms settling in reef areas are affected by the amount of siltation in the water. In addition, increased nutrient loading encourages the proliferation of algae that competes with corals. Terrestrial runoff has also been shown to depress immunity and alleviate chances of diseases in corals.

Proliferation of *Sargassum* algae can damage coral reefs. **TTC**

GLOBAL THREATS, LOCAL IMPACTS

In 1998, the reefs faced a threat at an unprecedented scale. Elevated sea surface temperature induced by an El Niño event triggered widespread bleaching that affected almost all coral species. Appearing pale white because of the loss of the important symbiotic algae from their tissue, the reefs transformed dramatically from a multi-coloured spectacle to a dull pale-white ghostly vision. Coral death was imminent if the loss had been prolonged, but corals could recover if the zooxanthellae were to be restored in time. As sea temperature returned to normal after three weeks, 80% of the corals recovered. Another widespread bleaching occurred in 2010, this time with 10% coral mortality, and yet another in 2016. Mass bleaching events have intensified and are more frequent. These climate change-related influences now add substantial stress to the direct on-going human impacts.



Due to prolonged high sea surface temperatures, corals start to bleach and appear white. **TTC**

Diving into Singapore’s past

Corals here are used for sclerochronology to assess historical coral growth in relation to environmental changes. In 2010, scientists reconstructed annual growth rates from cores of over 30 *Porites* colonies sampled around Singapore. They found that the average calcification rates have slowed by 17% since the 1980s, from 1.8 g/cm^2 to under 1.5 g/cm^2 of skeleton a year. If the current rate of decline continues, these corals may cease to contribute towards the building of the reef framework in 150 years.

The cause for the slow-down in growth rates of Singapore's corals is unknown although sea warming has been identified as a factor. Seas around Singapore have been warming at a rate of 0.07°C per decade. In 2010, the temperatures at several reefs around Singapore exceeded 32°C, one of the hottest in 100 years. Waters that are too warm cause significant stress to the corals and can lead to bleaching and mass death. **JT**

Heat stress caused corals around Singapore to bleach in 2010. Corals lose their symbiotic algae zooxanthellae when stressed, causing them to appear white or ‘bleached’. **JT**

Mortality induced by coral bleaching reduces the level of live coral cover on a reef. **HD**

As more carbon dioxide, the main industrial greenhouse gas, is released into the atmosphere, more of the gas dissolves in seawater to form carbonic acid. The resulting decrease in pH of seawater — about 0.1 units on the logarithmic scale recorded since the 1800s — leads to ocean acidification. This less-understood global-scale effect will impact coral reefs in very complex ways. Physiologically, the increase in acid

Dead *Porites* corals leave behind their skeleton that are eventually colonised by algae and other organisms. **HD**

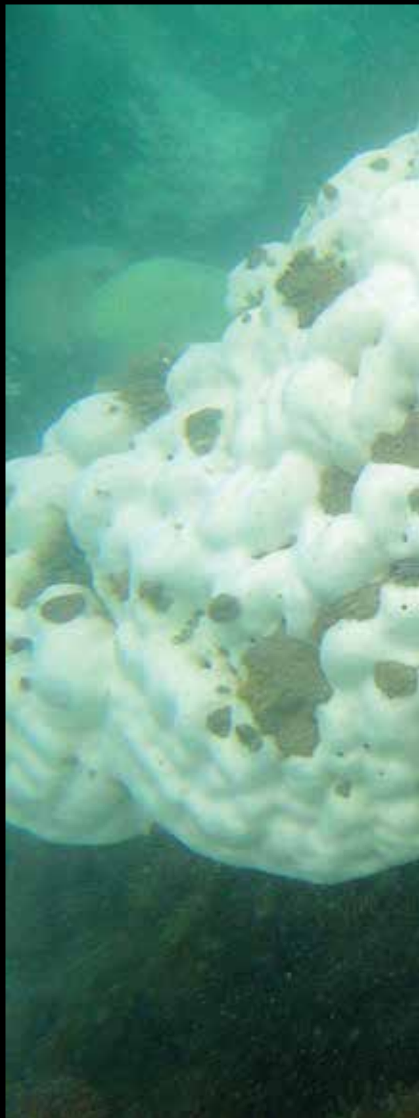
concentration in seawater makes it harder for corals to produce calcium carbonate to build their skeletons. Chemically, the acidity simply causes dissolution of limestone so that reefs are gradually eroded away. As with bleaching and disease, species differ in their abilities to adapt and acclimatise to lowered pH. Time is running out, and such global-scale problems now add a complex dimension to local stresses.

What makes Singapore's reefs resilient?

During short periods or low doses of stressful events such as elevated temperatures, pollution, and sedimentation, protective biochemical and cellular mechanisms are triggered in some marine organisms. These result in the production of protective enzymes and heat shock proteins that help living cells remain stable.

Scientists attribute the rapid recovery rate of corals from bleaching events to two important characteristics: resilience to chronic levels of low stress, and low susceptibility of symbiotic zooxanthellae in some of Singapore's coral species.

The constant exposure to stressors probably afforded some type of hardiness to coral species. Further, some coral species may have inherited specific clades (types) of symbiotic zooxanthellae that help their hosts overcome stressful events. This capacity for resilience is not unlimited however — these corals are taking longer with fewer recoveries in recent bleaching events. **BG**



Coral colonies such as this massive *Porites* sp. can be resistant to bleaching. **HD**

Threats against coral reefs, if not mitigated early, eventually lead to loss of species, or local extinction. Because corals constitute the main frameworks of reefs and many organisms depend on particular species for microhabitats, each extinction may have a more widespread effect than only the loss of the coral species.

In 1994, two coral species were considered endangered after they were not observed since the 1960s. These are the branching species *Stylophora pistillata* and *Seriatopora hystrix.* Interestingly, these species are not uncommon in other parts of the Indo-Pacific region. Their rarity in Singapore was a mystery. To the excitement of many marine biologists, a single colony of *Stylophora pistillata* was rediscovered at Raffles Lighthouse during surveys in 2006 and 2007. Unfortunately, the colony did not survive the mass coral bleaching event in 2010.

During the same survey of 2006 and 2007, 33 new records of coral organisms were discovered, increasing the number of known species in Singapore to 255. For its small reef area (~13 km^2), species diversity here is remarkably high compared to neighbouring countries, which are all part of the Indo-West Pacific centre of marine biodiversity. However, only about two-thirds of the total diversity has been observed in recent years. An exhaustive survey that includes the islands of Pulau Pawai, Pulau Sudong and Pulau Senang, will generate more accurate species occurrence data.

The last known remaining colony of *Stylophora pistillata* in Singapore did not survive the bleaching event in 2010. **KT**

FROM 'DOOM AND GLOOM' TO 'GROOM AND BLOOM'

Despite the shrinking reef area and on-going degradation, Singapore's coral reef biodiversity continues to persist, supporting more than 150 species of corals.

New species and new records of reef-associated organisms have been discovered by volunteers working alongside marine scientists. **HD**

Intertidal reef areas are natural classrooms for teaching. **HD**

In the late 1980s, the Singapore Reef Survey and Conservation Project was initiated through the collaboration of the Republic of Singapore Yacht Club, the Singapore Underwater Federation, and the Singapore Institute of Biology. Over 150 volunteer divers were trained to survey the reefs. The results were incorporated into a report identifying four broad clusters of coral reefs that deserve protection. It was not until the 2000s that a Blue Plan was developed, which finally resulted in the implementation of the Comprehensive Marine Biodiversity Survey. The CMBS, as it was referred to, was helmed by the National Parks Board (NParks) and the National University of Singapore (NUS). This effort lasted from 2010 to 2015. Surveys of all marine areas and of most marine organisms revealed many new species and new records.

The Singapore Blue Plan

Marine conservation advocates responded to the marine environment gap of Singapore's Green Plan by developing a Blue Plan. The first Blue Plan was submitted in 2001 to relevant government agencies through the Environmental Feedback Group, a Government Parliamentary Committee. It was an outline generic plan and no specific agency was put in charge of marine conservation. The opportunity to develop a revised Blue Plan came during the 2008 International Year of the Reef. Blue Plan 2 benefitted from the involvement of many partners and stronger scientific input. Scientific capacity and the number of concerned citizens have also increased. The National Biodiversity Centre (NBC) of NParks was also by now firmly established as the relevant government agency to deal with marine conservation. The submission of Blue Plan 2 in 2009 met with favourable response from the Government, and facilitated the implementation of the five-year CMBS programme.

In 2018, the Singapore Blue Plan 3 was launched. It called for concerned citizens and government agencies to collaborate on conservation action plans for imperiled marine ecosystems of the country. **CLM**

The number of marine conservation groups have increased over the years and they play a role in tackling pressing issues such as marine trash. **OSR**

Research support

Reef studies involve both field and laboratory investigations. Funding for coral reef research has increased steadily with the availability of grants from institutions of higher learning, and government and development agencies. There are no funding programmes dedicated specifically to coral reefs but there are a few for marine science. Most recent is the five-year S$25 million Marine Science Research and Development Programme launched in 2015 by the National Research Foundation. This is a large boost to the further advancement of marine science research and development in Singapore and a number of the initial research grants awarded focus on coral reefs or include corals. These are 'Adaptation and resilience of coral reefs to environmental change in Singapore', 'Physical and biogeochemical effects of sediment transport on coral reefs' and 'Ecologically engineering Singapore's seawalls to enhance biodiversity'. Projects that are in line with national initiatives strategic to sustainability such as biodiversity improvement of coastlines and better management of coral reefs will be implemented in collaboration with agencies like the Housing and Development Board (HDB), Jurong Town Corporation (JTC), Maritime and Port Authority of Singapore (MPA) and NParks. **CLM**

Scientific research has helped us understand the unique dynamics of Singapore's reefs. **DHI**

EXPOSING OUR REEFS THROUGH RESEARCH

With new technologies and more people involved in reef conservation, the more recent threats to coral reef ecosystems were averted. During the development of the Semakau Landfill in 1999, silt screens were deployed to reduce the impact of sediment damage to adjacent reefs. The screens block suspended sediments generated by the construction activity. Currently, most projects, including the expansion of the Pasir Panjang Container Terminal, utilise these barriers in combination with proactive reef monitoring carried out by biologists to mitigate the effects of reclamation.

Genes under stress

The biological instructions encoded in the deoxyribonuleic acid (DNA) of coral cells are converted into messages, known as transcripts, to carry out cellular functions needed for development, survival and reproduction. A collection of transcripts is called a transcriptome. By studying the entire transcriptome, scientists can determine how specific genes respond to particular environmental conditions. We examine the transcriptome-wide pattern of gene expressions of corals in Singapore to study the mechanisms driving their stress responses and recovery. We can use this information to understand how our coral reefs are better able to tolerate future changes to the environment. **RCPD**

Gene expression of corals such as this *Pocillopora acuta* colony is being studied over the course of coral bleaching and recovery. **RCPD**

Comprehensive Marine Biodiversity Survey, 2010–2015

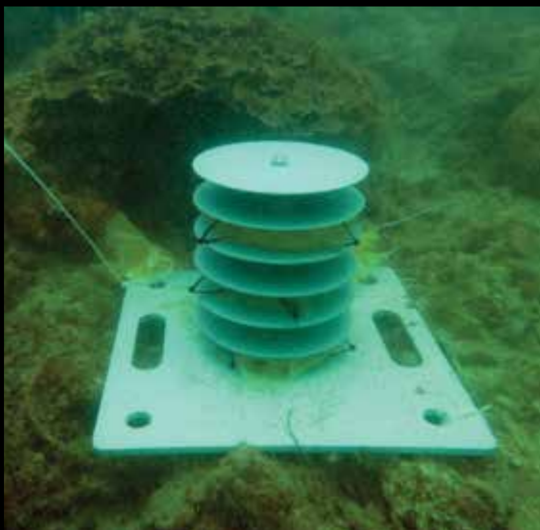
The CMBS was launched in November 2010 to take stock of marine life in the coastal waters of Singapore. Led by NParks and NUS, the five-year project was funded in part by corporate sponsors. Local marine biologists, invited international specialists, and more than 350 volunteers, surveyed and studied thousands of marine organisms.

They discovered more than 40 marine species new to science, and more than 120 species previously unknown to Singapore. These included sponges, sea anemones, flatworms, nematodes, sea slugs, shrimps, marine mites, copepods, hermit crabs, sea cucumbers, tunicates, and fishes. On-going analyses are expected to further increase these numbers.

Sieving for isopods after sunset during low tide on a reef in the Singapore Strait. **TKS**

A rectangular dredge was used to obtain specimens from the soft-bottom seabed in the Johor Strait. **TKS**

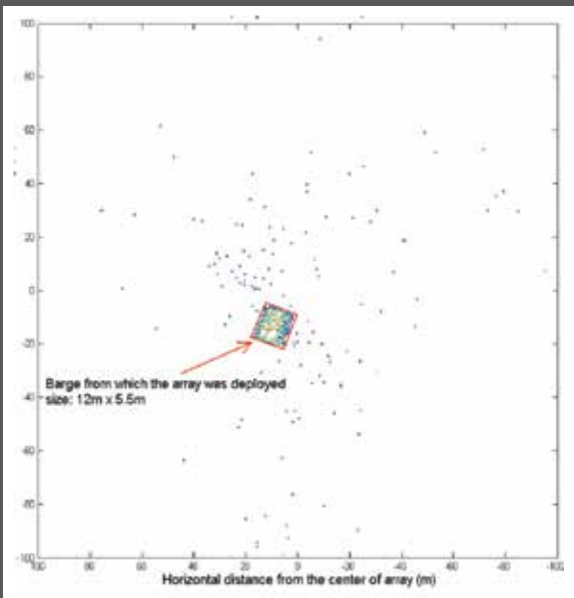
Can marine life be encouraged and sustained in Singapore? CMBS was a bold step towards understanding the living marine environment that has changed significantly due to coastal development. The results of CMBS will provide us with an unprecedented marine biodiversity baseline to address these efforts in an objective and scientific manner. **TKS**



Autonomous reef monitoring structures such as this one were deployed. **TKS**

Surveying coral reefs: seeing with sound

Dolphins and whales use echolocation to navigate and capture prey underwater. Using similar procedures, scientists use acoustics to survey the marine environment. However, commercial systems developed to classify seabeds are unable to classify benthic organisms or identify the shapes and skeletal densities of corals that can be used for conservation. In 2004, a joint team from the Acoustic Research Laboratory (ARL) in the Tropical Marine Science Institute (TMSI), and the Department of Biological Sciences in NUS, developed a custom acoustic sensor array for the classification of corals. The system consisted of an acoustic array of four sensors, and a digital camera. The camera was used to collect an image of a coral each time a sound was emitted and was later used for ground truthing. Researchers from ARL also developed a hydrophone array to map the position of snapping shrimps using the sound of their snaps as an acoustic source to produce images of targets in the water. With more development, acoustic techniques could lead to powerful methods to survey coral reefs with better accuracy of determining coral morphology and overall reef health. **PS, STM & KTB**



Distribution of snapping shrimp over an area in shallow water. **PS**

A research diver operating the acoustic sensor system. **PS**

Singapore's fish library

A team of researchers is hard at work to inventorise fish species in the seas of Singapore. More than 500 fish species are known to occur, and about half are associated with coral reefs. The team is obtaining samples for the Lee Kong Chian Natural History Museum (LKCNHM), where fishes are catalogued and referenced by scientists, just as in a library. The team also plans to build another library — one that utilises DNA information of these fishes — using a method known as 'DNA barcoding' in which specific genes (e.g. cytochrome oxidase I or cytochrome b) are systematically sequenced and compared for all species.

The yellow-bar sandperch *Parapercis xanthozona* (top) and the coral trout *Plectropomus leopardus* (bottom) are two fish species to be studied by the team. **JL**

Barcoding of the DNA is a reliable method to detect species that are highly variable between individuals, or highly variable throughout their lifespan. For example, many species of parrotfishes undergo sex change as they mature. These changes, from juvenile to adult, and from one sex to the other, include drastic changes in patterns and colours at different stages.

Another application of DNA barcoding is to discern between two different species that appear very similar — known as 'cryptic species'. Application of the DNA barcoding method in these instances can help identify new or unknown species.

Once a library of sequences of fishes is in place, researchers can sequence seawater samples to know the fishes present there based on trace materials, such as mucus and scales, in the water. The sequences obtained from seawater samples can be compared to the sequences in the library so scientists can identify the fishes present in the area. This method, known as environmental DNA (eDNA), can be used to biomonitor the fishes within our marine areas.

Although a difficult and tedious task, this inventory will allow easy cross-referencing of the species, their traits, associated environmental data, and DNA sequences. For this reason, the team comprises researchers with different expertise from NUS, Temasek Life Science Laboratory, NParks, and LKCNHM to achieve this ambitious goal. **ZJ & JL**

Adults and juveniles of the same species can appear different; Juvenile Harlequin sweetlips *Plectorhinchus chaetodonoides* at 44.8 mm standard length (top) and an adult at 167.5 mm standard length (right). **THH**

RESTORATION

Coral reefs in Singapore have been impacted from the effects of land reclamation and intensive coastal development since the 1960s. Ideally, conservation of marine habitats should be prioritised but realistically, intervention measures are necessary, as the pace of natural recovery cannot offset the degradation rate of coral reef habitats. Restoration and rehabilitation efforts are thus important in coral reef conservation.

Researchers have used a myriad of techniques in studies to determine how best to assist in the recovery of Singapore's reefs. These techniques can be broadly classified into two categories: physical or biological restoration. A combination of customised approaches involving several restoration techniques has been shown to greatly improve the recovery of impacted reefs. With more land reclamation planned over the next two decades, there remains a pressing need to explore varied methods to augment current restoration approaches.

Land reclamation along Pasir Panjang in the western coastline of Singapore *circa* 2011. **TTC**

Corals recovered from Terumbu Bayan and transplanted to a nearby reef during a salvage operation prior to land reclamation. **HD**

What is physical restoration?

Physical restoration of coral reefs focuses on re-instituting the structural complexity of these habitats through the use of artificial structures. Artificial reefs made of used tyres and concrete were first introduced off Pulau Hantu in 1989 to improve fish stocks. These structures supported 55 species of fishes over seven years, but corals did not readily grow on their surfaces because they were at depths of more than 10 m. From 2001-2003, modular fibreglass units were placed in shallow areas of reefs at Satumu, St. John's, Kusu, Lazarus, and the Sisters' Islands. These units provided elevated surfaces that encouraged corals to grow without being smothered or scoured by sediment and rubble. Within two years, these units were colonised by various algae species and corals from seven families. A decade later, a total of 29 coral genera from 12 families were recorded growing and reproducing on these units. The units also functioned as shelter and supported a source of food for many organisms including soft corals, sponges, sea anemones, fishes, echinoderms, crustaceans, and molluscs. **TTC & LN**

A fibreglass unit on the reef at Sisters' Islands in 2015, more than a decade after deployment. **LN**

What is biological restoration?

Biological restoration focuses on encouraging the re-establishment of corals within degraded reef areas. Since the early 2000s, researchers in Singapore have been rearing corals in nurseries, either at laboratories or on site, and then transplanting them to the various reef sites after growing to a suitable size. Over 3,500 coral fragments from 38 coral genera have been reared at on-site nurseries off Lazarus, St. John's and Semakau Islands. In 2007, more than 400 coral fragments were transplanted to reefs at Pulau Semakau and Pulau Hantu. Corals with branching growth forms (e.g. *Acropora* spp., *Pocillopora* spp.) are less suitable for transplantation, while others with massive or submassive growth forms (e.g. *Porites* spp.) continued to survive and grow after transplantation. **TTC & LN**

Research divers securing small naturally-occurring coral fragments on the frame of an in situ nursery at Pulau Semakau. **AS**

Coral fragments transplanted on a dead coral boulder at Pulau Hantu. **LN**

Genetics and coral restoration

Preserving genetic diversity is a primary goal in conservation biology but difficult to achieve in practice. Utilising Next-Generation Sequencing technology, scientists found that as few as five coral colonies could represent 50% of the genetic diversity from a reef in Singapore. This finding can improve the efficacy of restoration and transplantation efforts. For example, based on these findings, one would have to transplant or preserve only five, rather than 50, colonies of one coral species per site in order to effectively preserve the genetic diversity of the species. **LAR**

Turbinaria peltata, one of the coral species at Sultan Shoal's reef, being examined for genetic diversity. **LAR**

Gardening Singapore’s seawalls

Hard coral (top), soft coral and sponge colonies (bottom), more than three years after they were transplanted on the seawall. **LN**

Seawalls, which dominate much of Singapore’s shoreline, are characterised by harsh environmental conditions which discourage the colonisation and retention of desirable marine organisms. To enhance the biodiversity on seawalls, NUS researchers, together with HDB, pioneered methods to accelerate the establishment of reef-building organisms on these coastal defence structures. Living fragments of selected species of hard corals, soft corals, and sponges were first reared in nurseries, then transplanted to the intertidal surfaces of a seawall on Singapore’s northern coast.

In two years, successful transplants exhibited significant increases in size, with some carpeting entire granite boulders. These in turn provided alternative microhabitats for other fauna. The findings demonstrated that this was a viable management strategy to help boost the ecological value of the otherwise often sparsely populated seawalls. **LN & TKS**

Sustaining coral reefs in a busy port

In 2013, MPA commissioned the relocation of corals from Sultan Shoal, which will be affected by the Tuas Mega Port development. It also collaborated with NUS on a research project to restore degraded reefs and create reef communities in new habitats using the coral fragments generated from the relocation exercise. The fragments were reared in coral nurseries that were designed to reduce sediment accumulation and improve coral survival. After a year, more than 90% of the corals survived, grew larger and were transferred and attached to granite seawalls and degraded reefs. More than 900 fragments from 17 genera were transplanted and 422 m^2 of reef area was restored. To raise awareness of marine conservation efforts, volunteers were also trained to assist researchers in coral fragmentation, nursery maintenance and transplantation. The synergy between the public sector, public and academia was an important factor that contributed to the project's success. **SSQ & TTC**

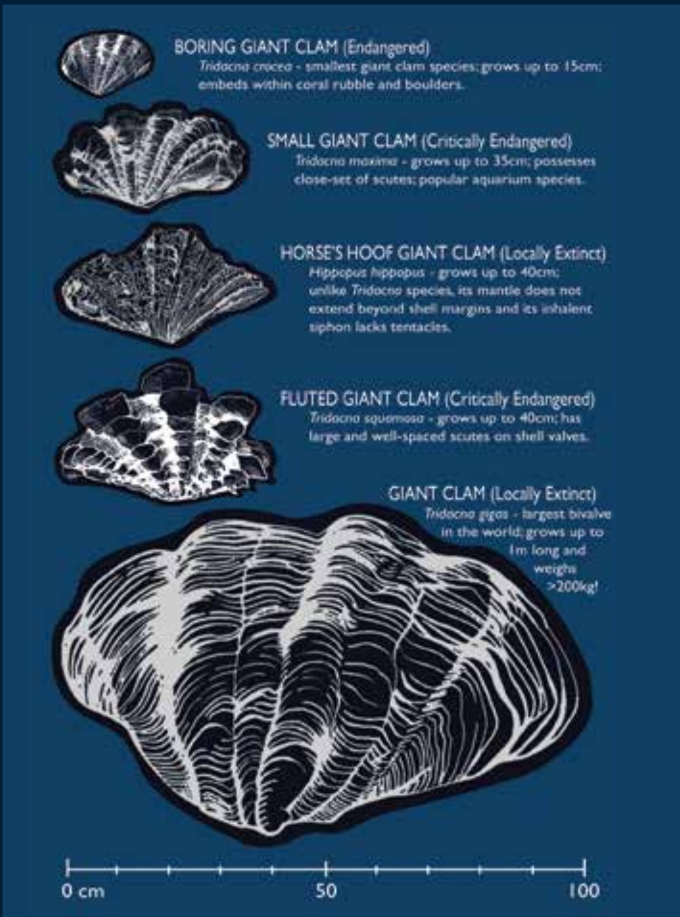
Coral fragments were reared in coral nurseries before transplantation. **Reef Ecology Laboratory**

Coral fragments transplanted to create new reefs on granite seawalls. **TTC**

Clamming up Singapore's coral reefs

Giant clams were once prominent inhabitants of coral reefs in Singapore but were intensively exploited for food, shell trade, and lime production over the past few decades. Of the five species that once populated our reefs, two — *Tridacna gigas* and *Hippopus hippopus* — are now locally extinct. The other three species — *Tridacna crocea, Tridacna maxima* and *Tridacna squamosa* — remain critically endangered. Continued degradation of reef habitats has caused the decline in giant clam numbers. Because these clams are important as food sources, shelter areas, and reef-builders, scientists proposed to repopulate local coral reefs with giant clams grown in laboratories. In 2011, with funds from NParks, researchers from NUS set up a hatchery at the marine station located at St. John's Island. Several cohorts of *T. squamosa* have been cultured and out-planted. With dedication and some good fortune, these majestic giant clams may yet have a chance to thrive in Singapore's waters again. **NML**

An adult *Tridacna squamosa* (shell length = 30 cm) covered with a variety of organisms, including sponges, ascidians, soft corals, encrusting algae and macroalgae. **NML**

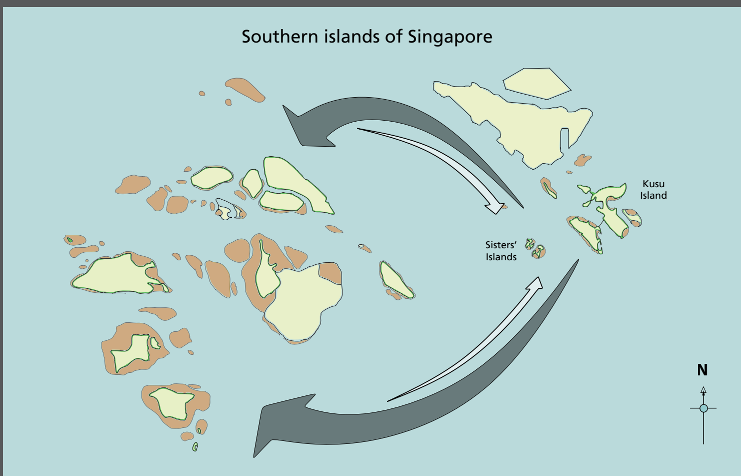


The five giant clam species recorded in Singapore's coral reefs, with their current conservation status (based on the Singapore Red Data Book). **LL & ZW**

Transplanting giant clams to Singapore's coral reefs. **NML**

Networks in the sea: the Singapore story

Mass spawning of many marine species in Singapore — hard corals, soft corals, sea anemones, sea urchins, and sea stars — have been documented from March to May. During this inter-monsoon season, the tidal regime drives the water body to and fro along the Singapore Strait, with a net southwest displacement of the water and the larvae carried within. Hydrodynamic model simulations of local larval dispersal have predicted that coral reefs upstream of the currents (e.g. the Sisters' Islands Marine Park [SIMP] or Kusu Island) are more likely to be source reefs that provide larvae to the rest of the reefs within the southern islands. The constant movement of the water body around Singapore likely has the greatest influence on local larval exchange patterns, as genetic tests for broadcast spawning species such as the hard coral (*Platygyra sinensis*), and the knobbly sea star (*Protoreaster nodosus*), showed near-panmixia (i.e. high exchange among populations). This dispersal pattern is likely similar to other broadcast-spawning species. Little is known however, of larval dispersal patterns in species which reproduce at other times of the year, or have different reproductive strategies. **TYC**



General source-sink dynamics among the coral reefs in the southern islands of Singapore. There is a net southwest movement of coral larvae during the coral spawning period as indicated by the thickness of the arrows. **TYC**

MANAGEMENT

The development of the Semakau Landfill in 1995 marked the first time protection measures were taken to reduce the impact of development on coral reefs. Sediment screens were deployed to minimise sediment smothering of the island's western reef. Many major coastal development projects that followed started to involve coral relocation and restoration initiatives, as well as real-time monitoring, to minimise impact on reefs. The establishment of NBC in 2002 extended the mandate of NParks to the marine environment and greater emphasis was given to environmental impact assessments and monitoring. More attention for reducing coastal development impacts on coral reefs is evident in the past 20 years.

Marching along with the country's history, this natural heritage has silently witnessed tremendous environmental change, and is revealing a resilience exemplified by the rich biodiversity that remains. However, its continued existence should not be taken for granted. Effective management is necessary to ensure that Singapore's coral reefs remain an integral component of the country's biodiversity.

The lost lone *Stylophora pistillata* colony at Raffles Lighthouse teaches a valuable lesson. The small size indicates a young colony, likely recruited recently from reefs outside of Singapore. Our corals are genetically well-connected to those of neighbouring reefs. If we are able to draw upon the collective will of the people and authorities to halt the declining conditions on Singapore's reefs, we may be able to reverse the decline. If this is achieved, lost species may grow and flourish in our waters again.

The involvement of the public is crucial in conserving Singapore's coral reefs. **OSR**

Singapore's first marine park

The official launch of SIMP in July 2014 — Singapore's first — is regarded as a major breakthrough in reef and marine conservation. The marine conservation journey has been a long one, which began before the country became an independent republic in 1965. It was a story of transformation from a confrontational to a conciliatory position between the conservation and development sectors. In February 2017, the parliament passed laws designating SIMP as a public park allowing for more effective protection especially over the foreshore and marine areas.

This 40-hectare park covers the area around Sisters' Islands including the western reefs of St. John's Island and Pulau Tekukor. The variety of habitats including coral reefs, seagrass and sandy shores in tight proximity, the high biodiversity, presence of rare and endangered species like giant clams and seahorses, and the reefs here as a source of coral larvae, all contributed to the justification for protection. Located within the busy port, SIMP will be

Sisters' Islands at low tide. **HPY**

Aerial view of Sisters' Islands. **NParks**

a sanctuary for reef and marine species. This will be supplemented by restoration efforts targeting iconic species such as giant clams. The Neptune's Cup Sponge (*Cliona patera*), believed to be globally extinct for over a century but discovered locally in 2011, will also be restored in the marine park.

Managed by NParks, activity programmes focus on education, outreach, conservation and research relating to Singapore's marine biodiversity. In July 2015, the Sisters' Islands Marine Park Gallery on St. John's Island was opened to complement its outreach mission. Numerous activities such as guided walks and dives are ongoing. Reef restoration programmes, such as Plant a Coral, Seed a Reef involve members of the public in coral conservation. **KT**

The Technical Committee on the Coastal and Marine Environment (TCCME)

The Technical Committee on the Coastal and Marine Environment (TCCME) was formed in 2007 to function as a technical arm for the Singapore Government in addressing issues related to the coastal and marine environment and facilitating effective management and conservation strategies. The committee is co-chaired by NParks and the National Environment Agency (NEA), and is represented by various government agencies and academic institutions. The TCCME secretariat is hosted at NParks' NBC.

TCCME provides technical advice on the impact of threats, including marine pollution and biosecurity on the coastal and marine ecosystems; identifies emerging trends in regional and international fora on coastal and marine environment issues; and undertakes research on the prevailing health of the coastal and marine ecosystems in the territorial waters of Singapore including monitoring of biodiversity, water quality and key environmental parameters. The committee also drives applied research work on the coastal and marine environment, and collaborates with relevant agencies and local/overseas experts on strategic projects.

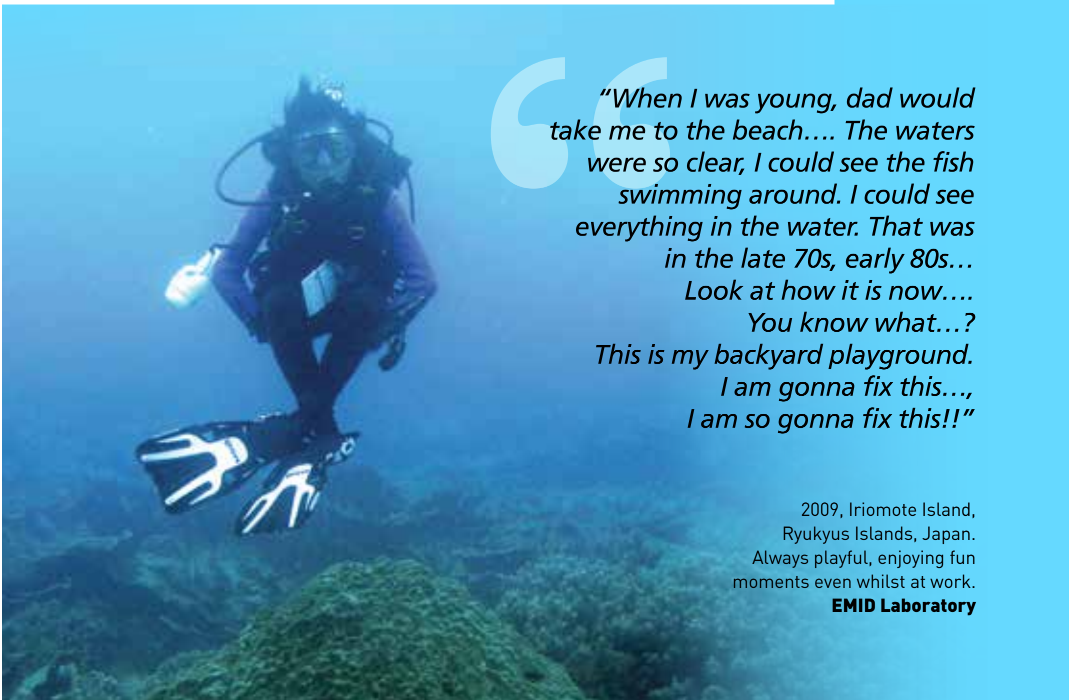
Government agencies have been actively supporting grassroots events. **OSR**

The collaboration between government agencies, academic institutions and nature groups is instrumental in marine conservation. **MPA**

Since its inception, TCCME has initiated over 40 research projects that address various knowledge gaps in the understanding and management of Singapore's coastal and marine environment. Moving forward, TCCME will continue to scan the horizon to identify risks to and opportunities for Singapore's marine environment, and to work with domain experts to undertake strategic research to continue Singapore's efforts to be a leader in marine environment protection. **KT & LC**

In Memoriam

Dr. Sin Tsai Min (March 11, 1970–July 30, 2017)



"When I was young, dad would take me to the beach…. The waters were so clear, I could see the fish swimming around. I could see everything in the water. That was in the late 70s, early 80s… Look at how it is now…. You know what…? This is my backyard playground. I am gonna fix this…, I am so gonna fix this!!"

2009, Iriomote Island, Ryukyus Islands, Japan. Always playful, enjoying fun moments even whilst at work. **EMID Laboratory**

This was the exact sentiment that drove Dr. Sin Tsai Min, or Tsai as she liked to be known, to persevere in her quest to improve the marine environment in Singapore. After completing her Bachelor's Degree at NUS, she worked for several years in aquaculture research, examining ways to enhance delivery of ascorbic acid in prawn feed. She then went on to complete her Doctorate Degree at James Cook University (JCU) in Townsville, Australia, where she focused her research efforts on understanding disturbance ecology on coral reefs. She then joined TMSI, where she remained until her demise. Tsai was involved with various marine environmental projects, from ship-fouling research, management strategies for alien invasive species and ballast treatment to eco-engineering designs for coastal reformation. She eventually found herself in charge of marine monitoring programmes and environmental impact assessments with various local governmental and non-governmental agencies including the Public Utilities Board (PUB), Jurong Town

Corporation (JTC), and HDB. In these monitoring programmes, Tsai actively directed research to understand ecosystem functions, coral reef ecology, biodiversity and conservation biology and ecological versatility and resilience. She demonstrated an in-depth understanding of physical oceanography, numerical and statistical modelling, geo-spatial science as well as informatics. She was a keen advocate of how all things are interconnected ('There is only ONE science!'). In 2012, she founded the Ecological Monitoring, Informatics and Dynamics (EMID) research group in TMSI, where research foci are organised into four main pillars; informatics, system characterisation, system understanding and ecological prediction. Her knowledge of Singapore's marine ecosystem was unprecedented and she armed herself with the skills to challenge paradigms and provide alternative hypotheses and solutions towards its conservation and management. The research that she steered provided the scientific insights for landmark government agency decisions on the management of reef ecosystems and sustainable water management. So few possess the skill to translate science to stakeholders but she did so with calculated diplomacy that earned their understanding, respect and trust. **ML, IB, KV, TYK, JT, OYX & EC**

2012, Changi beach, Singapore. Enjoying the sunset at Changi beach. **EMID Laboratory**

2008, Tanjong Hakim reef flat, St. John's Island, Singapore. Tsai on a reef walk with her staff (as part of her value-adding to staff's working experience). **EMID Laboratory**

6 EPILOGUE

Volunteers arriving at Sisters' Islands for an underwater cleanup dive. **OSR**

EPILOGUE

Our coral reefs flourished in an unspoiled environment well before the founding of modern Singapore. Early settlers commonly remarked on the beauty of the reefs seen through clear waters. Singapore's rapid development changed those pristine conditions. This is the price of development.

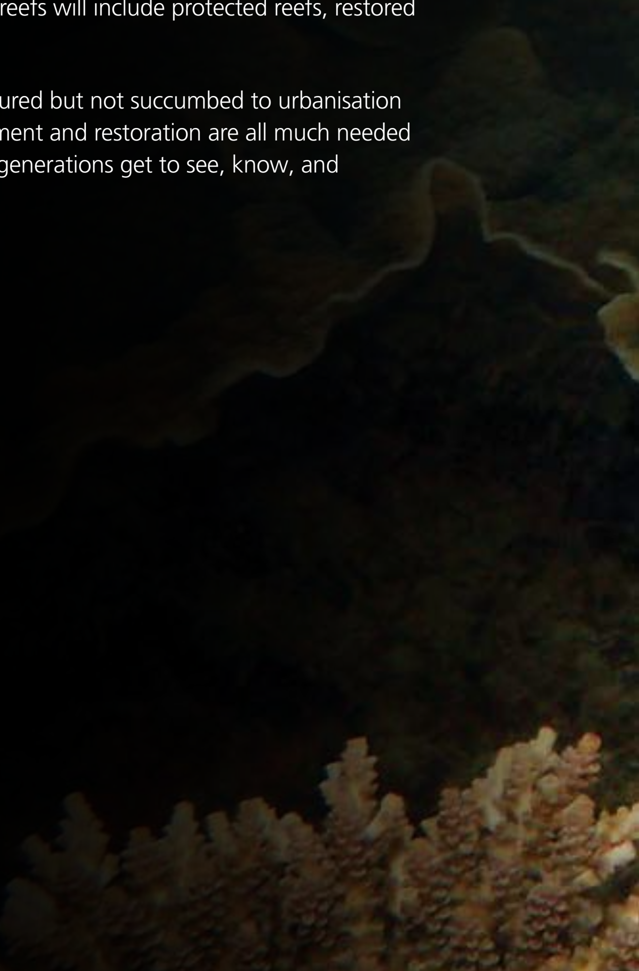
However, while the coral reefs were exposed to urbanisation impacts, they remain present as a major marine habitat. Yes, Singapore's coral reefs have diminished by 60% and the surviving reefs have coped with increased sedimentation for over five decades. They are also impacted by the new threat of sea surface warming, and in time to come, ocean acidification. The habitat has responded with gradual changes in the mix of species so much so that those commonly seen in the 1970s are being replaced by those that were less abundant before. This adaptation demonstrates a living habitat's ability to tolerate impacts and survive.

Large fishes, such as this pair of many-spotted sweetlips *Plectorhinchus chaetodonoides* are still found in our reefs. **JL**

Every species on a reef participates in this interesting ecological process and reveals interesting aspects of how reefs and people interact. Research is crucial to this understanding. The community of coral reef researchers and enthusiasts has expanded slowly but steadily. Through the combined efforts of many, we now have a better appreciation of the incredible biodiversity of our reefs, the amazing life processes and interesting aspects of reef resiliency. They are a rich treasure house of biological secrets waiting to be uncovered and, to re-emphasise, are right at our doorstep.

Our reefs did not just survive, they refused to die. But they need a lifeline. This is granted in increasing management effort, minimising impacts from coastal development, coral relocation, and the legislative protection to coral reefs exemplified by the declaration of Singapore's first marine park in 2014. Looking ahead, our coral reefs will include protected reefs, restored reefs and newly-created reefs.

Singapore's coral reefs have endured but not succumbed to urbanisation challenges. Protection, management and restoration are all much needed responses to ensure that future generations get to see, know, and appreciate our own coral reefs.



A staghorn damselfish *Amblyglyphidodon curacao* among corals at Pulau Satumu. **JL**

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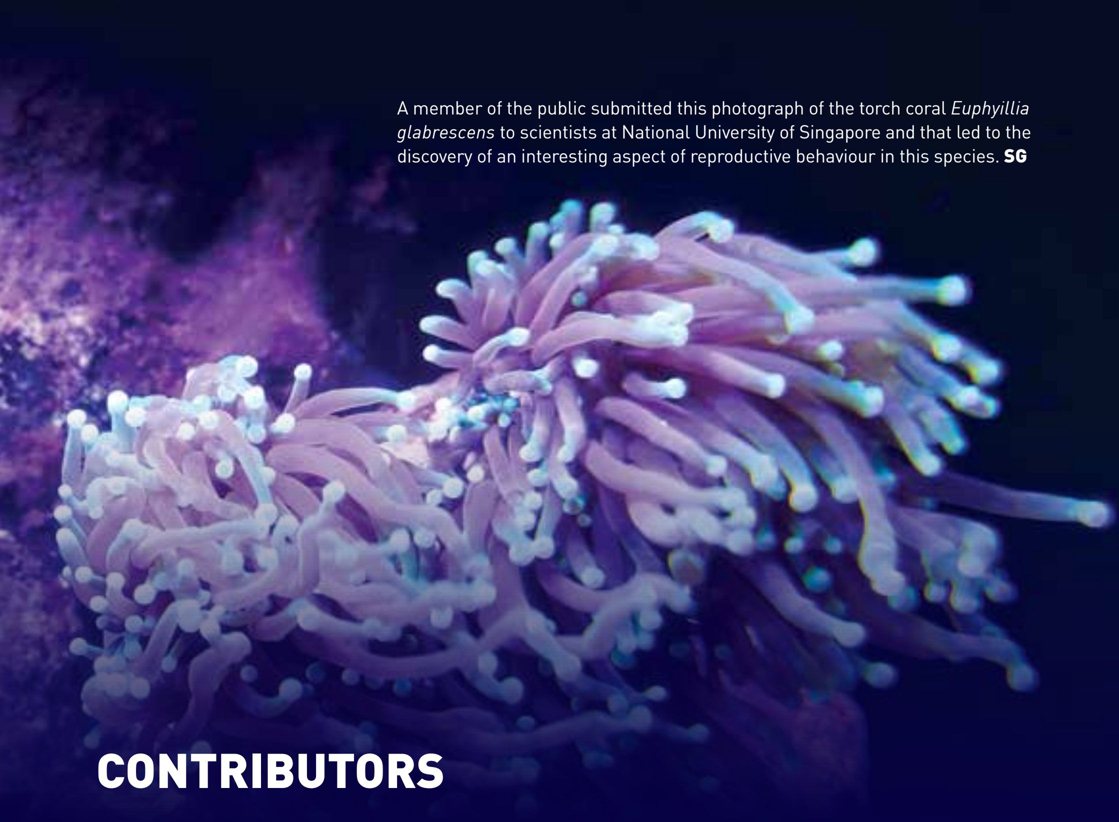
A false clown anemonefish *Amphiprion ocellaris* peers out at divers at Pulau Hantu. **HPY**



A member of the public submitted this photograph of the torch coral *Euphyllia glabrescens* to scientists at National University of Singapore and that led to the discovery of an interesting aspect of reproductive behaviour in this species. **SG**

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ABOUT THIS BOOK

Coral reefs are naturally endowed with high species richness. Despite impacts from decades of coastal development, Singapore's coral reefs persist as a sanctuary for many species. Perseverance of these reefs makes this natural heritage truly uniquely Singaporean. Coral reefs are interesting not only because they harbour a great variety of species, but also in the way that reef organisms interact through competition or cooperation. The habitat is visually spectacular because of the numerous colourful inhabitants. Many of these are well-camouflaged or extremely shy, and can be easily missed even with repeated visits to the same reef. The various biological processes operating in the reef system also offer many remarkable insights of habitat functions. Through field observations and research, much more is known of our reefs over the past several decades. Yet there is much more to discover. This book provides some aspects of the private lives of reef organisms and illustrates the significance of Singapore's coral reefs.

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