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Stephen Pincock is an author and journalist who has been writing about science for 20 years. His work appears in publications such as *Nature*, *The Lancet* and the *Financial Times*. He has written several books and edited *The Best Australian Science Writing 2011*.

DISCOVERING **SCOTT REEF**

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DISCOVERING

SCOTT REEF

20 YEARS OF EXPLORATION AND RESEARCH

James Gilmour, Luke Smith, Kylie Cook, Stephen Pincock

woodside

Australian Government

Australian Institute of Marine Science

Browse Joint Venture Participants

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Foreword

This book tells the story of the spectacular Scott Reef off the coast of Western Australia and how the partnership between resources company Woodside and Australia's scientists has created an unprecedented understanding of the ocean environment.

The story begins in 1971, when Woodside discovered the Torosa gas field beneath Scott Reef. Scientific interest in the area soon followed and Woodside has since supported research expeditions to Scott Reef. Starting in 1993 with the establishment of a long-term monitoring program that continues today, the Australian Institute of Marine Science (AIMS) has co-invested in much of this work.

Accurate environmental assessments of marine ecosystems like Scott Reef rely on a thorough understanding of the system and the conditions influencing it. But long-term investigations of this kind require significant investment of time and resources. Working with Woodside has offered scientists a unique opportunity to study this remote and normally inaccessible atoll. The work has produced an exceptional baseline for future environmental assessments, which was recognised in 2011 with an Environmental Award from the Australian Petroleum Production and Exploration Association. It's an example of how partnership between industry and the scientific community leads to better outcomes.

As a nation surrounded by oceans, maintaining the health of Australia's marine environments is critical to our economy and the industries that rely on its health. Our 'blue economy' was worth over $42 billion in 2009–10, and this is projected to double in size by 2025. That makes research in this field critical to securing Australia's future prosperity while conserving our unique marine ecosystems and biodiversity.

In this book, the authors share the discoveries and highlights of their research. It covers the early history of human visitation, through to the physical and biological oceanography, and the diversity of marine life that can be found at the reef.

The Scott Reef story will continue but the chapters here tell of the rich history of exceptional scientific research, the extraordinary remoteness of the reef system and its complex ecology and fascinating oceanography.

Professor Ian Chubb AC
Australia's Chief Scientist

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Organisations contributing to the scientific research presented in this book

Australian Institute of Marine Science (AIMS)

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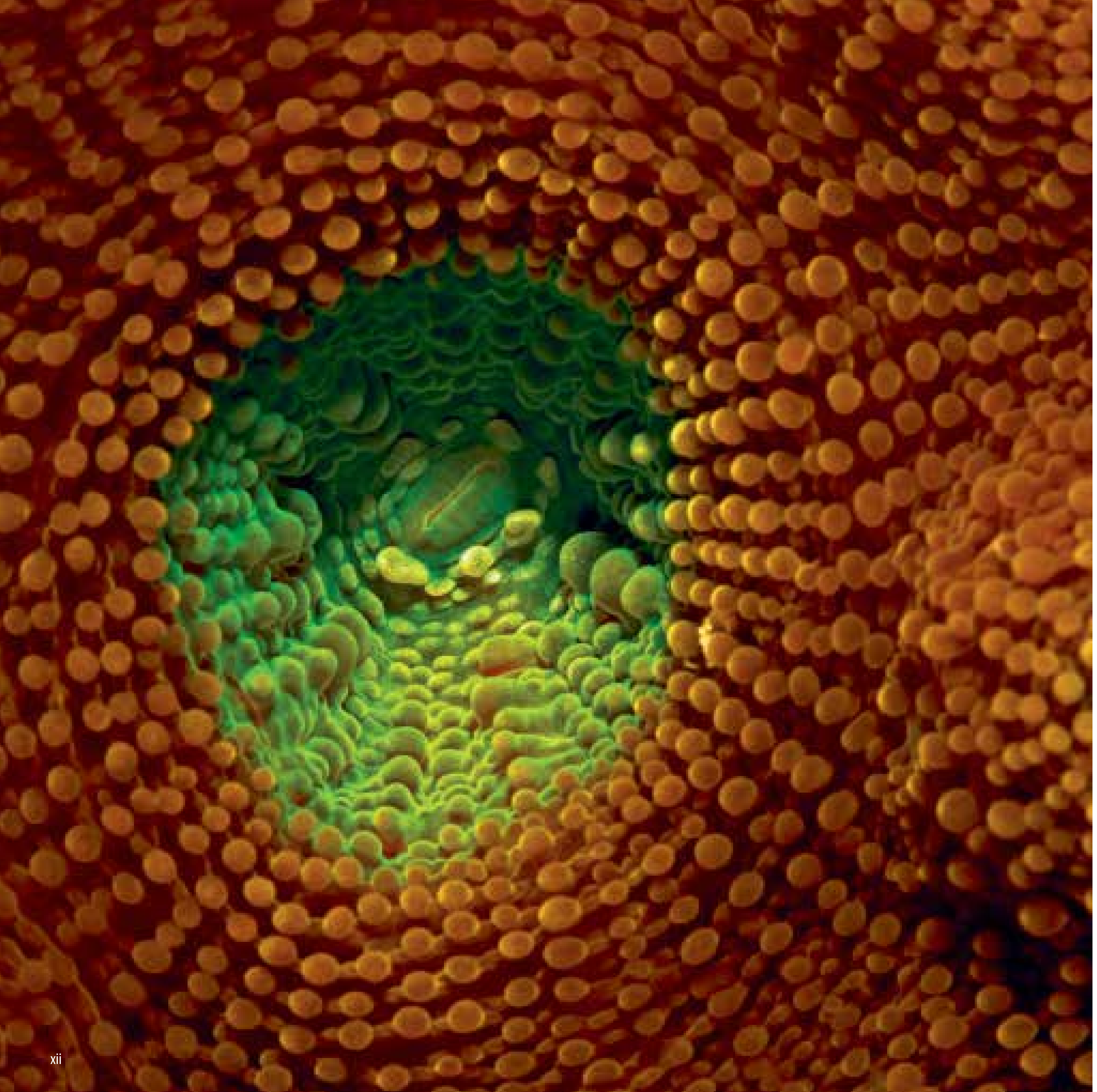
We would also like to acknowledge the scientists and support staff from all the organisations involved in the research at Scott Reef, and the operators and crew of the many vessels that have transported them to Scott Reef and back again. The master and crew of the RV Solander deserve a special mention for their commitment to their vessel, its work and the safety of all those on board.

Finally, we dedicate this book to Dr Andrew (Smiley) Heyward – a pioneer of coral reef research at Scott Reef and throughout Western Australia.



Introduction

Scott Reef rises steeply from the depths, near the edge of north-western Australia's continental shelf, far from the mainland and other reefs. Created from the accumulated skeletons of countless corals and algae, the reef's history can be traced back to the organisms that laid its foundations millions of years ago. Today, it is teeming with life, ranging from tiny single-celled organisms to the largest animals on the planet, all of which depend on Scott Reef's structure and biodiversity.

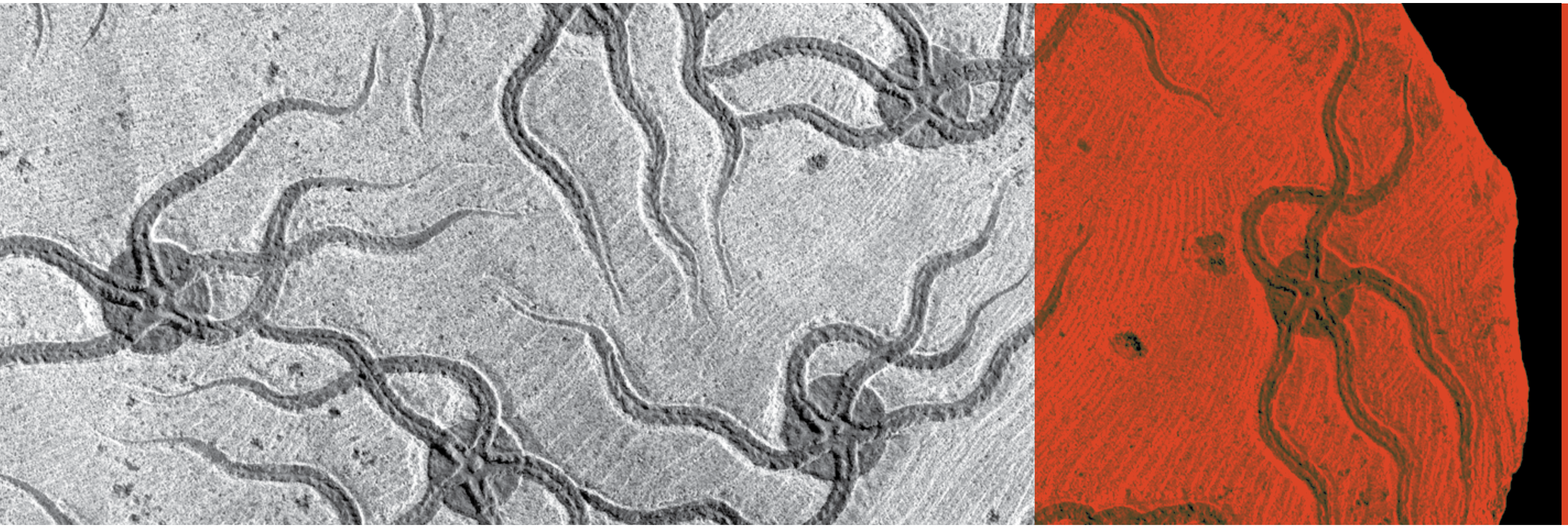
Scott Reef has a long history of human visitors, from the Indonesian fishers who have visited for hundreds of years, to exploration and scientific personnel in more recent times. Nevertheless, its remote location has protected it from many of the pressures affecting other reefs around the world, giving researchers a rare and valuable opportunity to study a healthy coral reef and the range of organisms that inhabit it.

Spanning almost 20 years, the research program at Scott Reef is one of the longest and most comprehensive investigations of a coral reef system in Australia. The work has largely been funded by Woodside Energy Limited and its joint venture participants, and the Australian Government through the Australian Institute of Marine Science (AIMS), but many other groups have also been involved. Scientists from more than 10 organisations have come together, spending hundreds of days at sea and thousands of hours under water. Their combined goal has been to better understand this unique ecosystem.

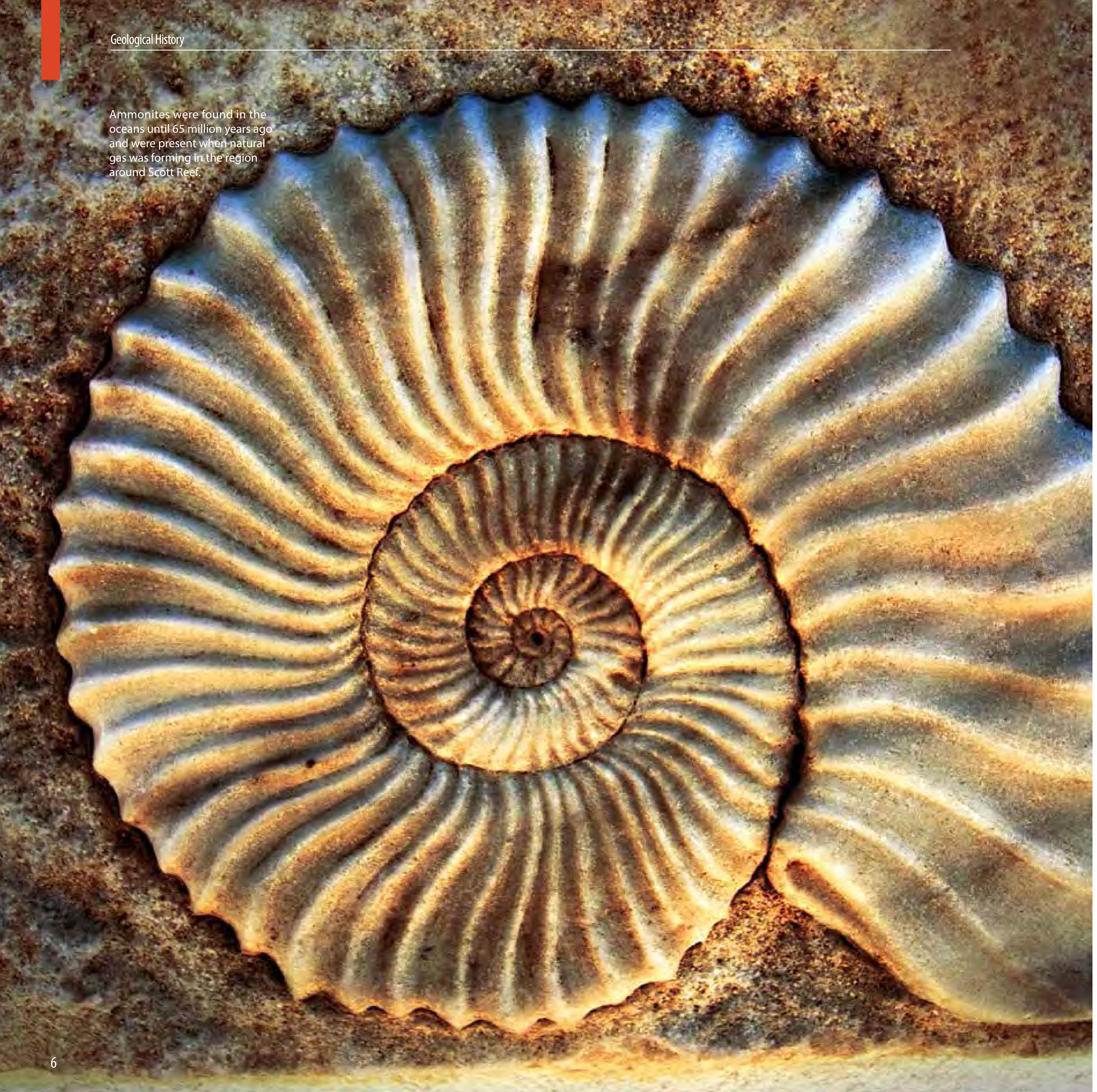
Over the years, the research at Scott Reef has evolved from a basic knowledge of the reef's organisms to a comprehensive understanding of a complex ecosystem. Early taxonomic surveys described the abundance of life at the reef, and then the introduction of a monitoring program documented how coral and fish communities varied across the reef and over time. More recently, the research was further expanded to include an intensive study of the reef's physical environment and the processes responsible for the changes in its biological communities. Together, scientists have created a detailed picture of Scott Reef – invaluable information when assessing how the reef may respond to future changes.

This book gives a first-hand account of the research conducted at Scott Reef. We hope it will allow the reader to embark on their own journey, and join us in celebrating the results of the collaborative research effort and the beauty and wonder of this isolated coral reef.

PAST AND PRESENT



Geological History



The story of Scott Reef began many millions of years ago, with the geological processes that slowly formed the reef's foundations, and then the reef itself. Many changes to the planet have occurred during this time – continents have drifted, sea levels have risen and fallen, new species have evolved and others have become extinct. Since the reef formed, it has experienced times of being exposed by low sea levels, and times of growth to keep up with rising sea level. Examining the history of Scott Reef over geological timescales has provided scientists with an important understanding of how the reef responds to changing sea level and different climates.

Living on the edge

Scott Reef rises from depths of up to 800 metres on Australia's continental slope, some 270 kilometres off the current coast of north-western Australia. Seen from the air, it is made up of two large adjacent reefs. The pear-shaped North Reef is a continuous loop, broken only by two narrow passages, while the horseshoe of South Reef is open to the north. A channel, two kilometres wide and up to 700 metres deep, runs between them. To the north-east, about 30 kilometres away, is the smaller circlet of Seringapatam Reef, whose narrow reef rim surrounds a lagoon approximately nine kilometres across.

The reefs are atolls – coral reefs that enclose lagoons. Millions of years ago, they began to develop at a high point of the subsiding continental slope. As the sea floor slowly sank, coral and other marine organisms built up layers of reef. Today, the surrounding sea floor is deep underwater, but the coral reef continues to grow and change. Exploratory wells drilled more than 4700 metres into the rocks below Scott Reef reveal a sedimentary history dating back to the Late Triassic period some 220 million years ago.

Hydrocarbon formation

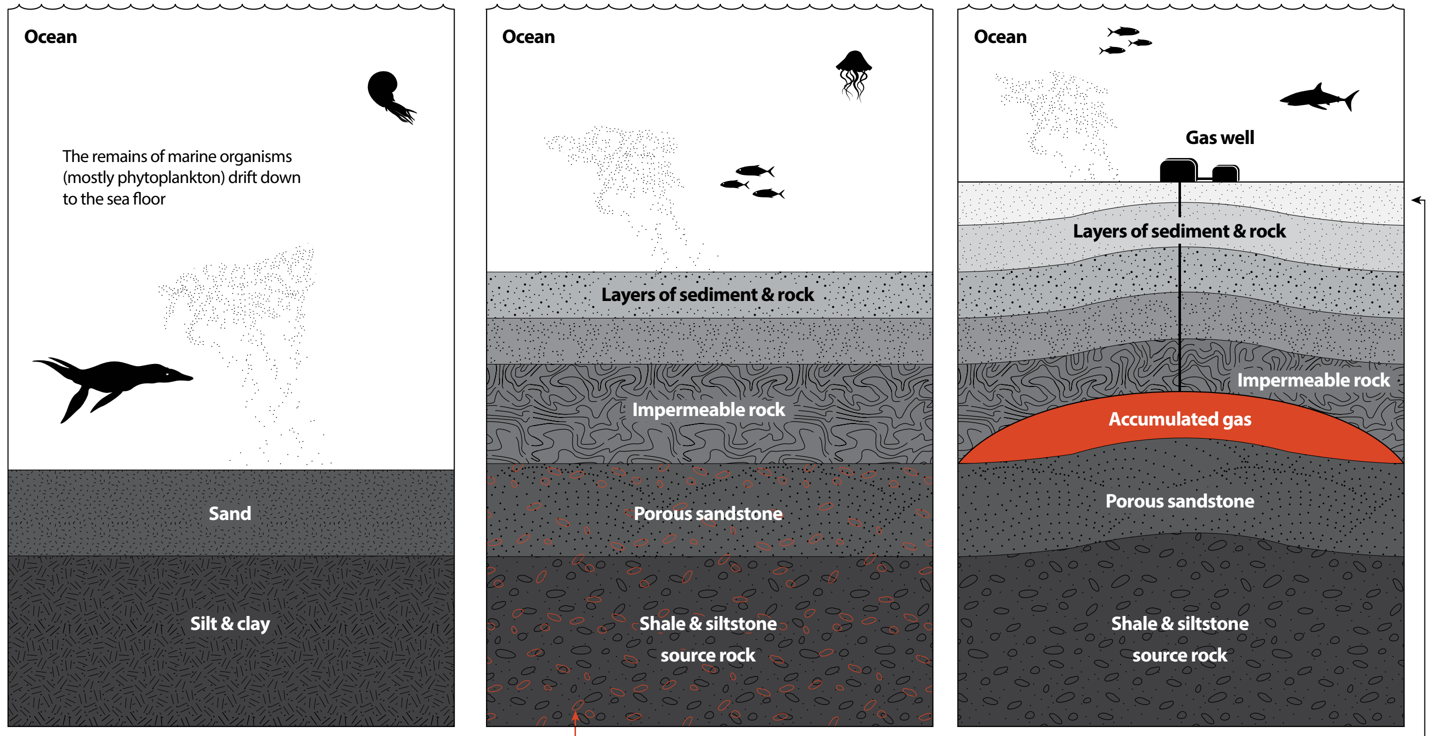
Two hundred million years ago, at the start of the Jurassic period and long before the reef itself existed, the area where Scott Reef is now was a broad flat plain near the northern edge of the ancient supercontinent of Gondwana. The landmass that is now India lay to the south-west, with an ocean to the north-west and north. Geological processes – which would ultimately lead to the breakup of Gondwana, with the opening of the Indian Ocean and the separation of what would become India and Australia – started to stretch this part of the Earth's crust.

Gradually, the sea encroached onto the ancient plain. Sand and silt carried by rivers were deposited in this shallow sea. The remains of many marine plants and animals, particularly tiny single-celled plankton, also drifted down to the sea floor. These sediments, and the organic matter they contained, were then buried by additional layers of sediment that accumulated above them. Eventually, compressed by the weight of the overlying sediment, they became sedimentary rock.

The thick band of sediment and rock overlying the organic-rich Jurassic rocks acted as a blanket, holding in heat that flows continuously from the interior of the Earth. Over time, this heat transformed the organic matter into hydrocarbon compounds – the components of natural gas. The hydrocarbon molecules, squeezed by immense pressure out of the shale and claystone 'source rocks' into porous rocks (such as sandstone), percolated upwards through the tiny pore spaces between the sediment grains until they encountered an impermeable rock layer. If the structural form of the impermeable layer was right, the trapped hydrocarbon molecules may have travelled large distances until they accumulated to form concentrated deposits of oil or gas.

At Scott Reef, the natural gas accumulation is located about four kilometres below the seabed, at temperatures of nearly 200 degrees Celsius, and is made up of gas molecules that formed 50 to 100 kilometres away.

Hydrocarbon formation beneath Scott Reef began 200 million years ago – long before the reef existed. An accumulation of natural gas now sits four kilometres below the sea bed.



200–170 million years ago

160–65 million years ago

Remains of marine organisms are buried under additional layers of rock and sediment, and begin to be subjected to high temperatures within the Earth.

65 million years ago to today

Starting 65 million years ago, many layers of carbonate rock were laid down near Scott Reef, creating suitable conditions for the formation of natural gas deep below the sea bed.

Once formed, natural gas percolated upwards, becoming trapped and accumulating beneath a layer of impermeable rock below Scott Reef.

A reef is born

The first tropical coral reef structures in the area we know today as Scott Reef began to form about 15 million years ago, during the Middle Miocene period. This was a time of relatively warm global climates and the oceans were home to a great diversity of cetaceans – the relatives of modern day whales and dolphins. The ancestors of many forms of marine life, including the reef-building corals, were also present.

Scientists have discovered evidence of these reefs within layers of rock now hundreds of metres below sea level. By the end of the Middle Miocene, a barrier reef, atolls and patch reefs existed along the continental margin near Scott Reef. However, by 10 million years ago, many of these reefs had become extinct, drowned by rising sea levels. The cooling climate may have reduced the growth rate of corals and other reef-forming organisms, which failed to match the rising sea level. Many ancient reefs were simply too far underwater for corals and other light-dependent organisms to survive.

In addition to the changing sea level, the edge of the continental shelf was also beginning to subside, carried deeper by the shifting of the continents. The reef continues to subside today, at around 30–40 centimetres every thousand years – a rate that is easily matched by the growth of this healthy coral reef.

Today, Scott and Seringapatam Reefs are the only atolls that remain in the area, having survived many changes in sea level and ongoing subsidence of the continental shelf. They are one of three oceanic reef systems in the wider region, the others being the reefs of the Rowley Shoals to the south, and the Ashmore Reef system to the north.

Reef growth

Like all coral reefs, Scott Reef is built from the skeletons of a range of plants and animals, predominantly hard (scleractinian) corals and plants such as calcareous algae. The hard calcium carbonate skeletons these organisms produce remain behind long after they have died.

Corals are the best-known reef-building organisms, although their biological characteristics are not always easily understood. The organism we recognise as a coral is, in fact, thousands of tiny individual polyps, similar to sea anemones. The polyps grow together in a colony, building a hard skeleton around themselves. To survive and grow, reef-building corals rely on tiny symbiotic algae that live within their tissues and convert sunlight into energy.

As each generation of coral dies, its remains contribute to the growing reef structure, forming a limestone base upon which new generations grow. This layering process allows reefs to keep pace with changes in sea levels that occur over thousands of years, remaining near the ocean's surface where there is plenty of sunlight.

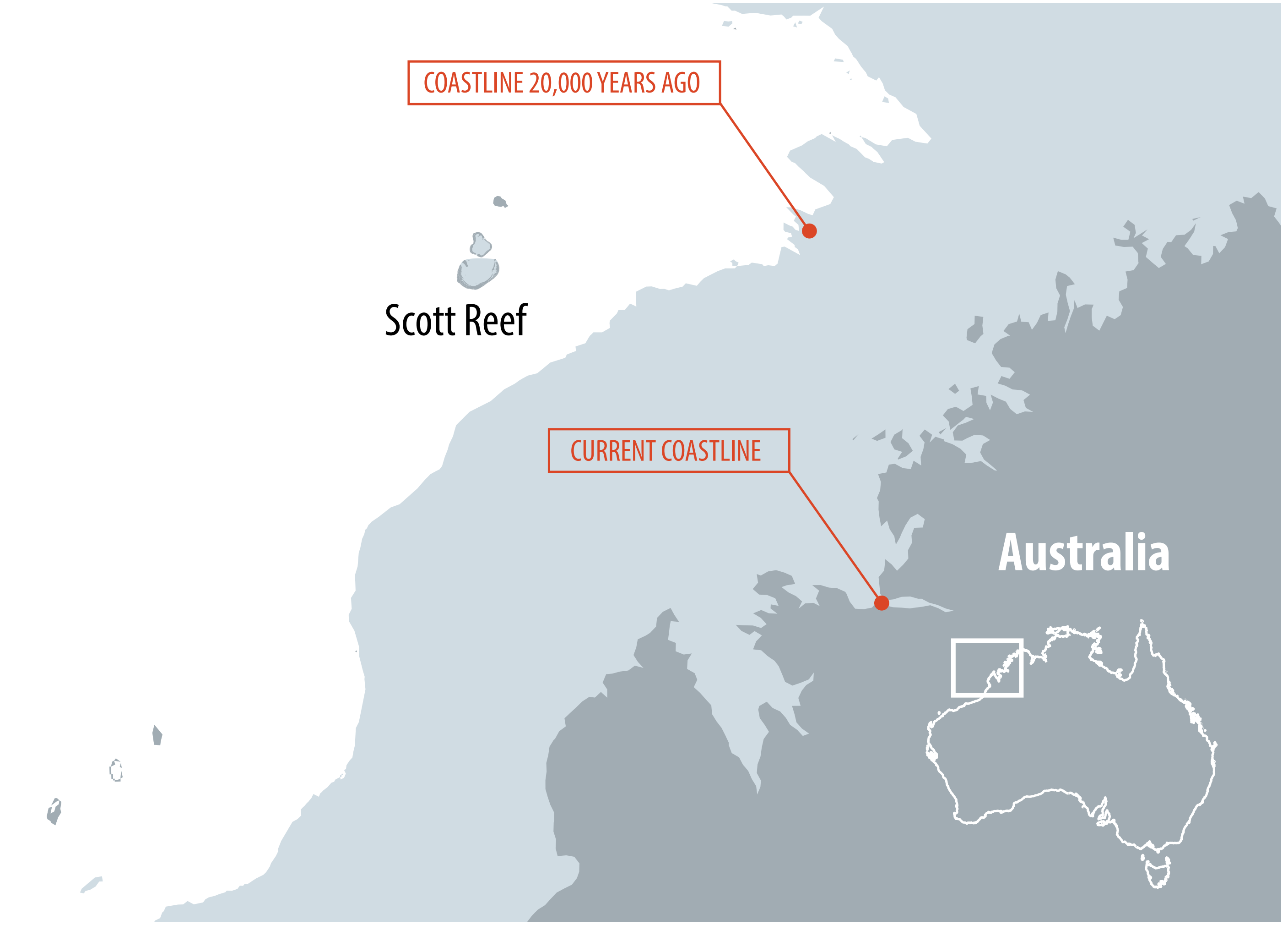
By extracting long cores from the reef and examining the layers within them, scientists have investigated Scott Reef's growth more closely. The cores have revealed that during the past 400,000 years the reef has gone through five significant phases of reef growth, each 30–40 metres thick, responding to rising sea levels during periods when the Earth's climate was warmer.

During colder, glacial periods in the Earth's climate history, when ocean levels were lower, the surface of the reef platform was exposed above water. In fact, for thousands of years the reef was a steep-sided rocky island, standing between 50 and 125 metres above the sea. Researchers have found evidence of these times – thin layers of hard, cemented limestone that formed over the reef, along with a pause in coral growth while the reef was not under water.

Twenty thousand years ago, at the peak of the last 'glacial maximum', sea levels around Australia were approximately 125 metres lower than they are today. At that time, the coastline would have been hundreds of kilometres further offshore than its current location, although the plants and animals would have been similar to those we know today. The reef would have been less than 100 kilometres from the shore – today it is around three times that distance.

The cores also revealed rapid periods of growth, more evidence that Scott Reef has kept up with rises in sea level. Since the start of the warm interglacial period 11,000 years ago, Scott Reef has grown about 35 metres.

The skeletons of millions of calcareous algae (top) and corals (bottom), deposited in layers, form the basis of Scott Reef.



Around 20,000 years ago, sea levels were 125 metres lower than today. At this time, Scott Reef stood high above the sea as a steep-sided rocky island, and experienced a pause in growth that scientists have observed in the layers within the reef structure.

The reef today

Altogether, North Reef, South Reef and Seringapatam cover some 650 square kilometres of potential coral reef habitat, at depths down to 70 metres. After millions of years, these reefs stand as monuments to changing climate and sea level over geological time scales. Their ability to withstand these changes also highlights the resilience that coral reefs have historically exhibited to climate and sea level fluctuations over these periods. Undoubtedly, Scott Reef will continue to change, although how it will keep pace with future rises in sea level remains to be seen.

Human History

Many traditional fishing vessels make the voyage to Scott Reef from Indonesia each year, using technology that has remained relatively unchanged since the 1600s.

Hundreds of nautical miles from land and without vegetation or fresh water, Scott Reef has never been the site of a permanent settlement. Yet for more than 300 years, humans have been regular visitors to the reef – first in search of food and mother-of-pearl, and more recently for exploration and research. Fishing vessels have travelled from Indonesia for hundreds of years, eventually joined by European ships exploring the region. In recent decades, visitors have had a different purpose – to explore the natural gas reserves in the area, and to investigate the reef's diverse biological communities. Today, a range of vessels converge on Scott Reef, drawn together by its natural wealth and beauty.

Sharks, sea cucumbers and mother-of-pearl

The tall, angular sails of traditional Indonesian fishing boats are a familiar sight to scientists who visit Scott Reef. Dozens of these small wooden vessels make the voyage from Indonesia between July and October each year. The boats set a southern course using local landmarks before navigating over the open ocean to Scott Reef, using little more than a rudimentary compass and the stars.

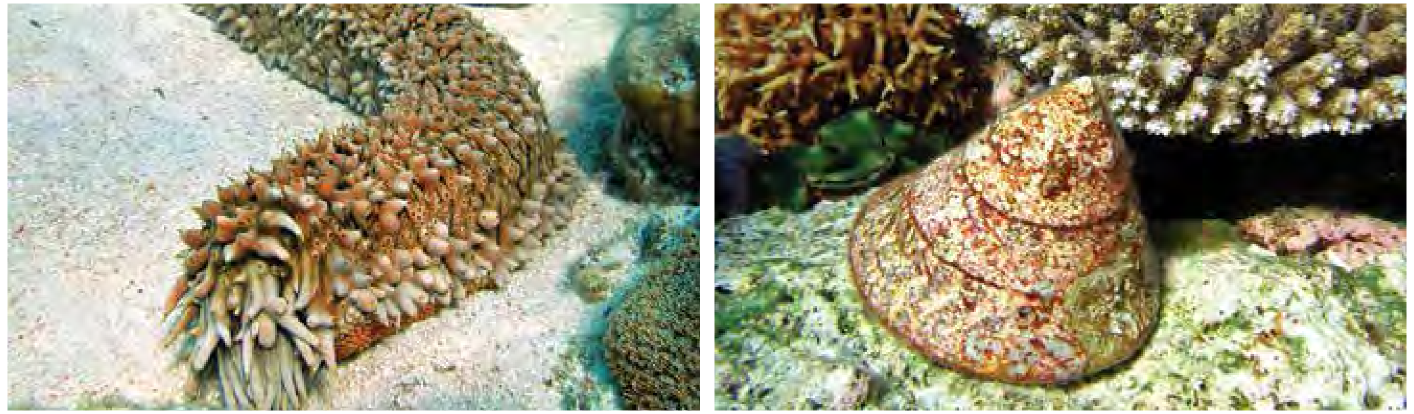
Often their first destination is Ashmore Reef, where they stop to replenish their stocks of water before continuing south. On reaching Scott Reef, the fishers gather trochus shells – whose iridescent interiors are used to make mother-of-pearl buttons – sea cucumbers, and the shark fins that are a prized delicacy in parts of Asia.

Each of these tiny wooden vessels carries a crew of around 10 fishermen. These men spend weeks at the reef, living on rice and water carried from home, and the fish they catch each day to cook over fires on the deck. During the peak season, up to 80 boats may visit the reef, and the number of fishers reaches into the hundreds.

Every day, they collect their catch by walking over the reef at low tide or free-diving to harvest prized species of sea cucumber and trochus. In doing so, they are carrying on a way of life that has changed little in more than 300 years.

For centuries, such fishermen or trepangers – 'trepang' is the Indonesian word for sea cucumber – were the only regular visitors to Scott Reef. In 1974, Australia and Indonesia entered into a Memorandum of Understanding that recognised this long history, acknowledging rights of access for traditional Indonesian fishers in a small area of Australian waters.

The voyage from Indonesia to Scott Reef is not without its risks, including dehydration and deadly storms and cyclones. The simple graves of several trepangers on Ashmore Reef and on Sandy Islet at Scott Reef bear testament to these dangers. But the benefits of these fishing expeditions are clearly considered to outweigh the risks. Dried sea cucumbers and shark fin sell for a high price, and by surviving at sea, fishermen ease the pressures on meagre food resources at home during hard times.



Sea cucumbers (left) and trochus (right) are harvested by fishermen who have been visiting Scott Reef for hundreds of years. A variety of sea cucumber species are processed and sold as food, while trochus shells are valued for the iridescent interiors of their shells.

Mutineers, smugglers and international tension

While Indonesian trepangers have long seen value in journeying to Scott Reef, the same cannot be said for Western sailors. The lack of fresh water on the reef meant that, generally speaking, it was a place best avoided.

The first accurate recording of the reef's position seems to have been made in 1801, by HMS Vulcan, under the command of Captain Peter Heywood. Heywood had been aboard the HMS Bounty during the infamous mutiny against William Bligh some 12 years earlier, but was pardoned by King George III. With that behind him, Heywood went on to become a respected charter of the oceans, the career that eventually saw him record Scott Reef's position.

A decade later, the Scottish hydrographer James Horsburgh reported that Heywood named the reef after the man who was at the masthead on Heywood's vessel at 1pm on February 22, 1801 when he saw the breaking waves amid the open ocean. For his part, Horsburgh thought the famed English explorer William Dampier had actually sighted the reef much earlier, but historians suggest it was in fact Seringapatam Reef, some 23 kilometres further north, that Dampier had sighted.

During the 19th and 20th centuries, the status of the reefs and islands of the Timor Sea became increasingly important. In the 1840s, American whalers discovered that there were large deposits of guano on islands in the north-west Kimberley region, and within decades the valuable substance was being taken from a number of offshore islands, including Ashmore Reef and Browse Island.

With money to be made, American and British interests negotiated the sovereignty of the reefs, with Britain eventually annexing Ashmore in 1878 and Cartier Island in 1909. According to one report, the crew of the British cruiser Cambrian hoisted their flag at Ashmore Reef, singing the national anthem and firing a 21-gun salute.

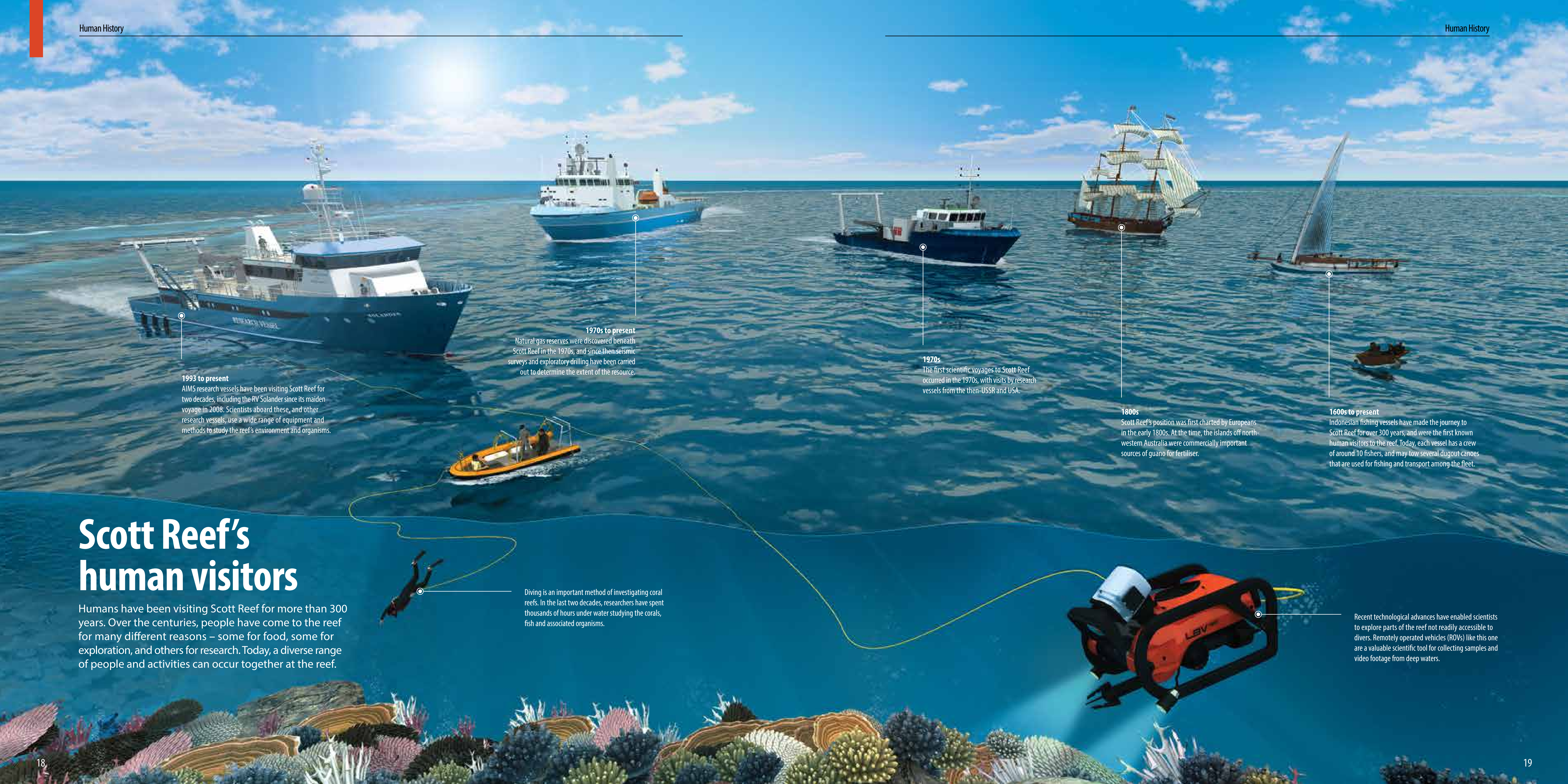
In the early 1900s, newspapers reported on claims of illegal poaching in the region. In 1911, a gunboat commissioned to carry out patrols of the north-west waters apprehended two schooners fishing at Scott Reef. The captains were charged with smuggling and their schooners released once they had paid their fines by selling their catch of trochus shell. The fines were apparently refunded later because Scott Reef had not yet been declared part of Australian waters – it was not until 1924 that the reef was declared part of Western Australia.

The wreck of the Yarra

Roughly 70 metres from the edge of Scott Reef, and visible at low tide, is the wreck of the Yarra, a 490-tonne iron barque built in 1870. Today, from a distance, the wreck can barely be distinguished from the reef. Over the 120 years since the ship was wrecked, it has slowly rusted away and been broken apart by waves.

The ship came to grief in January 1884, en route from Lakes Island in the Gulf of Carpentaria to England, with a cargo of guano. The vessel struck Scott Reef during a cyclone, and in the midst of the storm, all aboard had to abandon ship. Given that the gale had washed away the ship's boats, they were forced to lash together a makeshift raft. Remarkably, after 13 days at sea they reached Browse Island some 170 kilometres to the east. Even more remarkably, all survived.

Since the 1800s, many sailing ships (inset) have visited Scott Reef, both for exploration and while collecting guano at other reefs in the region. The Yarra was wrecked on the reef in 1884 and its remains can still be seen at low tide.



Scott Reef's human visitors

Humans have been visiting Scott Reef for more than 300 years. Over the centuries, people have come to the reef for many different reasons – some for food, some for exploration, and others for research. Today, a diverse range of people and activities can occur together at the reef.

1993 to present
AIMS research vessels have been visiting Scott Reef for two decades, including the RV Solander since its maiden voyage in 2008. Scientists aboard these, and other research vessels, use a wide range of equipment and methods to study the reef's environment and organisms.

1970s to present
Natural gas reserves were discovered beneath Scott Reef in the 1970s, and since then seismic surveys and exploratory drilling have been carried out to determine the extent of the resource.

1970s
The first scientific voyages to Scott Reef occurred in the 1970s, with visits by research vessels from the then-USSR and USA.

1800s
Scott Reef's position was first charted by Europeans in the early 1800s. At the time, the islands off north-western Australia were commercially important sources of guano for fertiliser.

1600s to present
Indonesian fishing vessels have made the journey to Scott Reef for over 300 years, and were the first known human visitors to the reef. Today, each vessel has a crew of around 10 fishers, and may tow several dugout canoes that are used for fishing and transport among the fleet.

Diving is an important method of investigating coral reefs. In the last two decades, researchers have spent thousands of hours under water studying the corals, fish and associated organisms.

Recent technological advances have enabled scientists to explore parts of the reef not readily accessible to divers. Remotely operated vehicles (ROVs) like this one are a valuable scientific tool for collecting samples and video footage from deep waters.

Human History

Resources and research

Until the late 20th century, only sporadic scientific attention was paid to the rich ecosystems of Scott Reef and the other reefs, banks and shoals that dot the broad continental shelf off north-western Australia.

In 1963, Woodside, an Australian-based oil and gas exploration company, was awarded exploration permits over 367,000 square kilometres of ocean off Western Australia's north-west coast. This included what is now known as the Browse Basin.

Initial seismic surveys in the late 1960s identified the area near Scott Reef as a prospective site. A drilling campaign just off Scott Reef in 1971 led to the discovery of the Torosa gas and condensate field. The field lies in part beneath Scott Reef, and over the decades Woodside, as operator of the Browse Joint Venture, has conducted a range of seismic surveys and drilling campaigns in the area to further appraise the Torosa resource.

Meanwhile, the first taxonomic collections from Scott Reef also took place in the 1970s. Scientists aboard the US Research Vessel Alpha Helix and the USSR Research Vessel Kallisto both catalogued specimens from the reef. In 1984, researchers from the Western Australian Museum carried out extensive surveys to sample fauna on the reef flats, lagoon and outer reef slopes of Scott and Seringapatam Reefs.

In 1993, the Australian Institute of Marine Science (AIMS) conducted a comprehensive survey of coral and fish communities at Scott and Seringapatam Reefs. The following year it established a long-term monitoring program designed to assess changes within the reef's shallow water coral and fish communities. The monitoring program continues today, with co-investment by the Woodside-operated Browse Joint Venture, and is one of the longest and most comprehensive coral reef monitoring programs in Australia. From 2008 to 2011, AIMS and other research institutes conducted a much more detailed and multidisciplinary research program at Scott Reef, with the goal of gaining a deeper understanding of the processes influencing the ecology of the reef, and the relationships between different habitats.

In the past 20 years, research at Scott Reef has involved a dozen organisations, hundreds of scientists and many years of cumulative ship time. Today, Scott Reef is among the most intensively studied coral reefs on the planet.

Exploration by the oil and gas industry began at Scott Reef in the 1970s, and has continued in parallel with scientific research.

Operational Challenges

A full day's steaming from the nearest port, Scott Reef's remote location makes it one of the most spectacular, and most difficult, coral reefs to study.

Scott Reef's remote location is a powerful draw for scientists wanting to study a coral reef system that is isolated from the effects of modern society. However, that same remoteness poses logistical difficulties and safety concerns. Scientists have conducted many surveys of the reef, using research vessels, aeroplanes and instruments deployed for months at a time, to study a multitude of organisms in vastly different environments. Each of the research methods they use – from visual observations to satellite tags – comes with its own challenges.

First things first

Getting to Scott Reef is never easy. Most research trips begin with a flight into Broome, where scientists board the vessel that will carry them to the reef and be their workplace for several weeks. Four or five hours after departing, the Kimberley coastline disappears from view. Night falls and passes, the sun rises again, and still the boat steams through the open ocean.

Around 24 hours after leaving the dock at Broome the engines finally slow. A few waves breaking on the shallows of the reef and an area of paler green water are the first clues that the destination is at hand. Broome is now about 425 kilometres to the south and the closest mainland 270 kilometres to the south-east. The horizon all around is flat and blue. For the scientists on board, it is time to get to work.

Of course, the journey to Scott Reef really began months before boarding the research vessel. Working in such a remote and potentially hazardous location requires extensive planning and experience. Research vessels can spend up to four weeks at the reef, requiring a significant list of provisions and scientific equipment. Even freighting pallet-loads of equipment to the wharf in time for departure can be a challenge in itself, with delays due to road closures a relatively common occurrence in this remote region. Forgotten supplies must be done without, as the round trip back to civilisation takes more than two days.

The researchers themselves also need considerable training before travelling to such an isolated place, including qualifications in first aid, diving and survival at sea. Thorough evacuation and emergency response plans are also critical to trip preparations. A commitment to safety is vitally important at Scott Reef, where advanced medical care is many hours away. This commitment to safe science has earned the Scott Reef Research Project two Commonwealth safety awards.

Even with all the preparations undertaken before visiting the reef, no qualification can guarantee that a visitor is suited to long periods at sea. The idea of spending weeks diving in tropical waters may sound wonderful, but it is not unheard-of for people to join a research trip only to discover – too late – that they suffer from seasickness. Others may struggle with working for hours on the back deck in tropical heat or with being immersed in water, day after day.

Life at the reef

Once at the reef, researchers use a variety of techniques to collect their valuable data. Some work relies heavily on scientists venturing underwater, using SCUBA (self-contained underwater breathing apparatus) or SSBA (surface supplied breathing apparatus), which require a small mountain of equipment and careful preparation. Compressors, air cylinders, breathing apparatus, communication units, buoyancy control devices, hundreds of metres of air hose, and myriad personal dive equipment must be maintained in optimal condition, checked and certified to minimise the risks of breathing underwater.

Scientists and their support crew use small boats to access the shallow areas of the reef. Each afternoon, they return to the research vessel to process the samples and data collected during the day's work.

In many situations, diving is not an appropriate method of research. Divers are generally restricted to shallow depths and can spend only limited time each day underwater, so studying deep water corals or collecting data over long time periods require different approaches.

In these situations researchers rely on alternative methods, including the use of remotely operated vehicles (ROVs) to collect samples from deep water organisms, and towed cameras to describe their communities. Environmental conditions are also monitored with instruments mounted on the research vessel's hull or deployed on the reef.

To make the most of a visit to Scott Reef, scientists will often deploy instruments that stay on the reef for months at a time, automatically recording data. This is one way to overcome the challenge of studying an isolated place, but is not without its own problems.

Electronic equipment can develop faulty connections in the harsh marine environment, or there may be difficulties in recovering instruments from the depths if their release mechanism fails. Equipment may disappear following severe storms and cyclones, or may be souvenired by other visitors to the reef, human or otherwise; reef fish have been known to bite off coral tags and sharks have damaged noise loggers. Given the effort required to deploy this equipment, considerable foresight is required to ensure sufficient data are obtained.

ROVs are used to describe and sample deep water communities, such as those as deep as 70 metres in the South Reef lagoon. ROVs transmit real-time video data back to the surface and have a moveable arm which can be used to collect samples.

Weighted metal frames carrying various scientific instruments are lowered to the sea floor, where they record data continuously for several months before being retrieved for data collection and maintenance.

Battling the weather

Scientists at Scott Reef live by the daily weather forecasts delivered through satellite email or fax, and the skipper's intuition. Work is shut down during periods of rough weather, so teams must be ready to adjust their work plan according to the prevailing conditions and make the most of calm periods. Currents, tides, wind and swell all require consideration. Working on the moving platform of a vessel or under the water in rough seas can make the simplest tasks difficult or even dangerous, so efficiency and safety considerations are paramount.

Moderate weather can make certain tasks impossible, but severe weather events like tropical cyclones are best given a wide berth. Tropical cyclones are common in the region around Scott Reef between November and April. Historically, many shipwrecks occurred during cyclones, and they remain a serious threat to modern mariners. Early warning services are closely monitored while at Scott Reef and early action is taken to avoid the path of tropical cyclones.

Diving operations are shut down during rough weather, but crew must be constantly vigilant. Squalls of wind and rain can hit within minutes of first sighting, and cause sudden changes in working conditions.

RV Solander

Since 2008, the Australian Institute of Marine Science has undertaken more than 25 voyages to Scott Reef aboard the RV Solander, a purpose-built, steel hulled research vessel. The vessel provides a home and workplace for up to 18 researchers and support crew, enabling them to work in remote areas like Scott Reef for weeks at a time.

Equipped with a 'moonpool' tunnel that allows instruments to be mounted below the hull to collect data while underway, four-tonne capacity winches and an eight-tonne capacity A-frame for deploying large equipment into deep waters, the RV Solander is a 35 metre floating laboratory and workstation.

Working from the RV Solander are four inflatable boats with outboard motors, which take teams of scientists into shallow reef areas where diving operations take place.

Operating and maintaining the vessel is the job of the six crew members who take care of navigation, winch and crane operations, stores of food and fuel, and mechanical maintenance, while also assisting the researchers in their tasks. The skills of the marine crew are vital for the safety and efficiency of the expedition. They can spend six months of the year on board so the RV Solander becomes a home away from home – they are constantly welcoming a new team of scientists. The crew know their vessel inside and out and without their skills, research would be impossible.

Diving safely

There are inevitable dangers when humans venture out of their natural environment to explore beneath the sea. Diving has evolved over many years since the days when basic equipment meant divers often had short life expectancies. Today, diving is a precise science in itself, with researchers well aware of the risks and equipped to avoid them.

Today, the use of modern equipment and dive tables minimises the risk of diving. These allow researchers to stay underwater for several hours a day without harm, but they must also consider other factors to avoid diving-related illnesses.

Researchers can now expect to dive safely for many years without accidents or health problems. Nevertheless spending time underwater still carries risks of decompression illness or 'the bends', which results when bubbles of nitrogen gas form within the diver's body as he or she ascends to the surface.

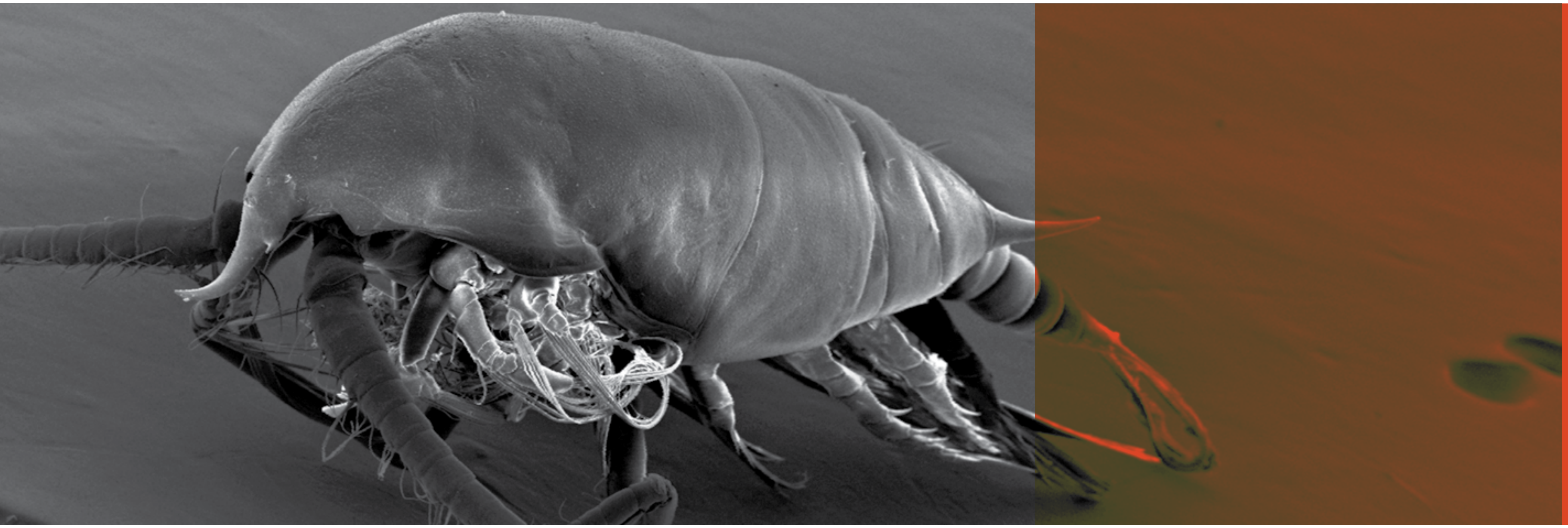
The risk is minimised by using conservative dive tables that provide guidelines for safe dive times at a range of depths. However, every person is different and divers can still get the bends while following the guidelines. Treatment for this illness is re-compression within a specialised chamber for several hours, allowing the bubbles to be absorbed back into the body tissues and then slowly cleared from the system. A re-compression chamber with accompanying medics and technicians is aboard the research vessel, ready to administer such treatment.

One of the first questions divers are asked by friends or family is 'aren't you afraid of sharks?' Most divers are wary of marine creatures – particularly those with sharp teeth – but usually have positive experiences with sharks. Reef sharks inhabit the Scott Reef area, but they are generally timid and less than two metres long. Most divers enjoy a sighting of these perfectly adapted creatures in their natural environment.

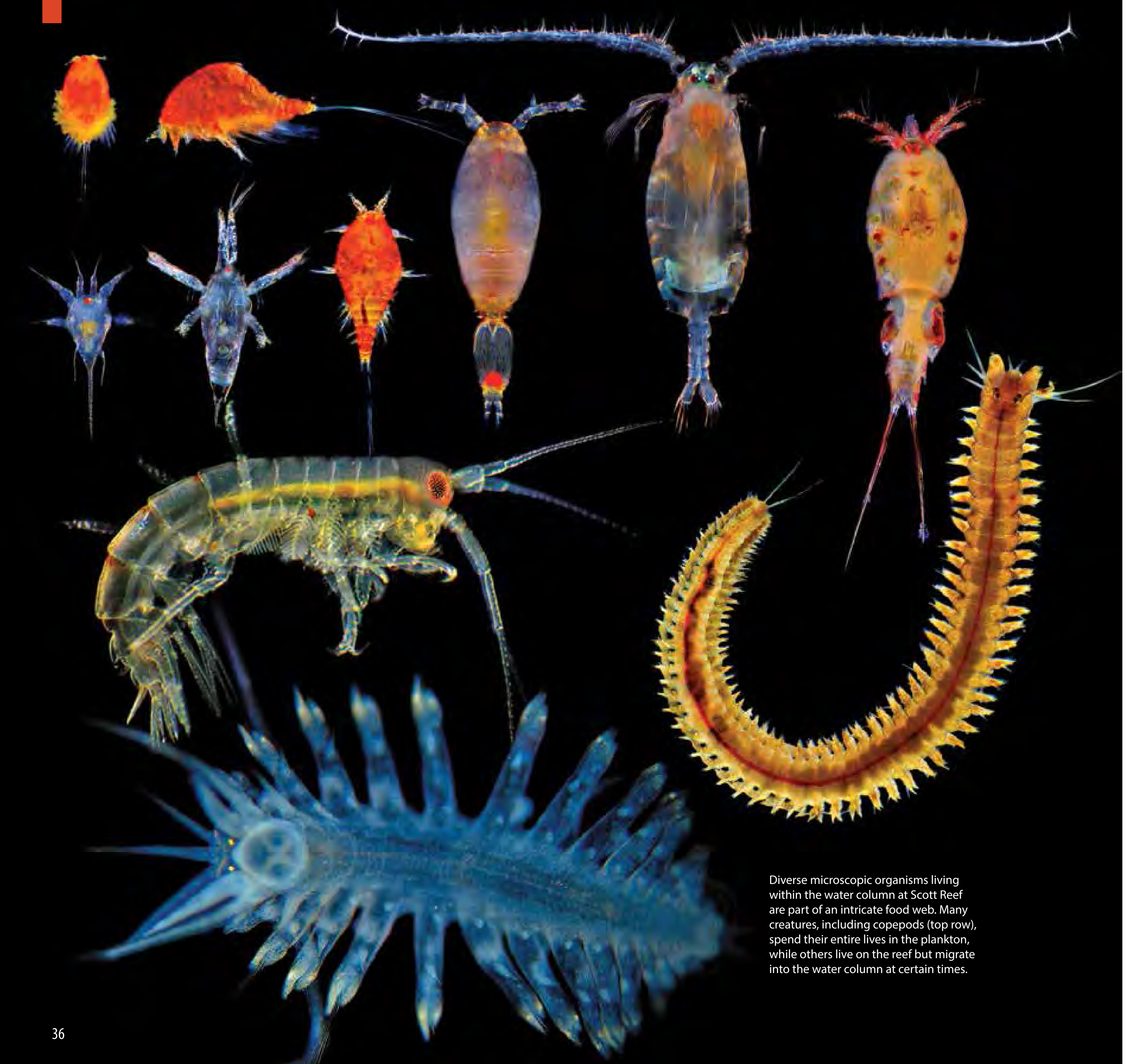
Other creatures have a lower profile but can be just as deadly. The sea snakes that are abundant at Scott Reef are venomous, but bites to divers are rare. Sharp-toothed moray eels, venomous stonefish and other dangerous creatures also live on the reef. However, divers cover themselves in protective gear, knowing to avoid rather than provoke such creatures. In thousands of dives at Scott Reef, no-one has ever been bitten or stung.

Sea snakes are common at Scott Reef, and have a venomous bite. Fortunately for divers, they are often inquisitive but rarely aggressive. Six species of sea snake have been found at Scott Reef.

ENVIRONMENTAL CONDITIONS



Oceanography



Diverse microscopic organisms living within the water column at Scott Reef are part of an intricate food web. Many creatures, including copepods (top row), spend their entire lives in the plankton, while others live on the reef but migrate into the water column at certain times.

Scott Reef's rich ecosystem depends on the water in which it exists. By studying the ocean's movements and temperature, its chemical makeup and biological properties, oceanographers have painted a detailed and sometimes surprising portrait of the aquatic environment that surrounds the reef. Huge waves within the water column peak when they arrive at Scott Reef and channel cold, nutrient rich water into the southern lagoon. These nutrients are utilised by a vast abundance and diversity of planktonic organisms engaging in a microscopic battle of life and death – zooplankton feed on phytoplankton, and phytoplankton die from viral infections – all within a single day.

Emerging from the deep

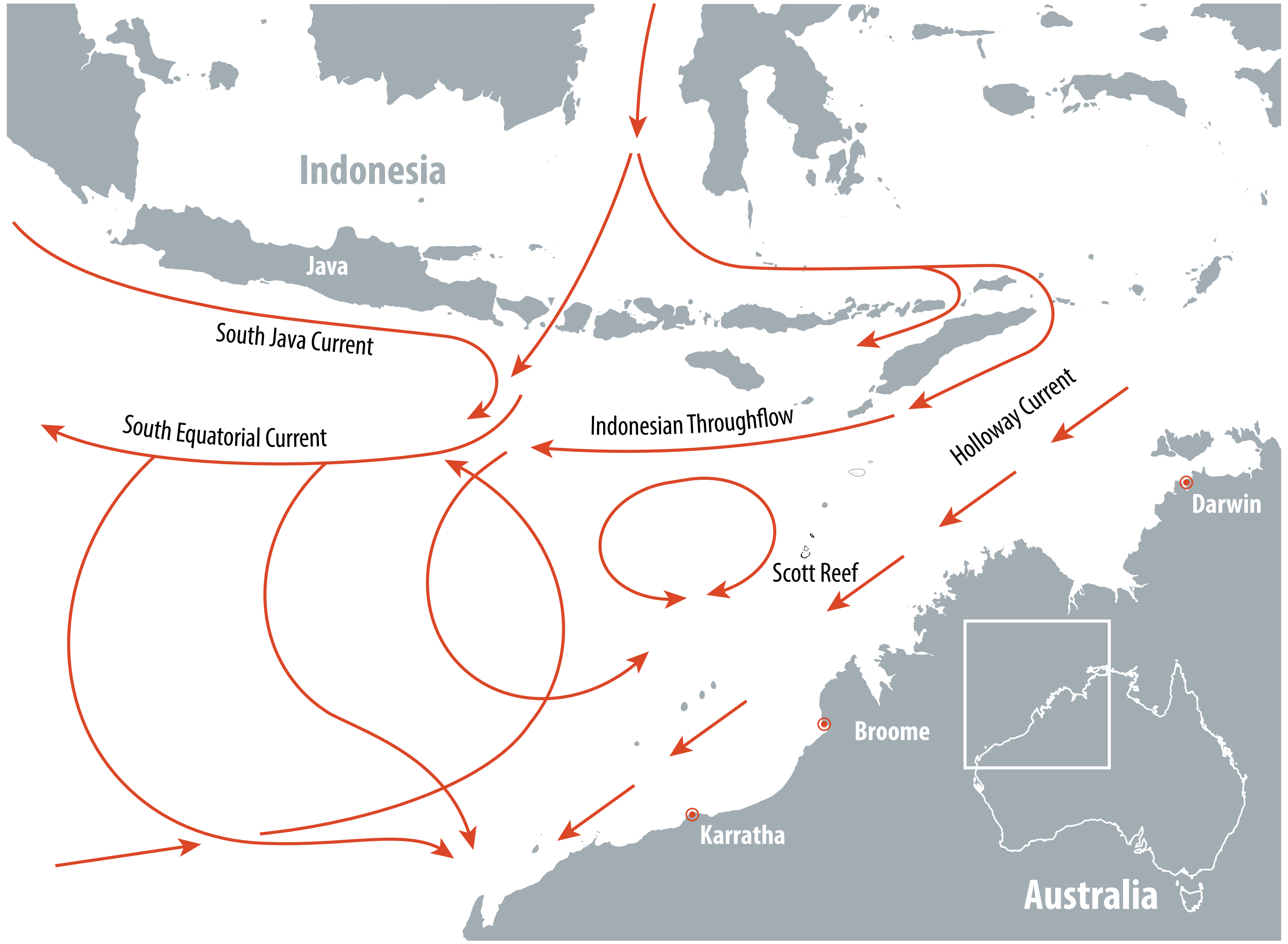
Rising from great depths and surrounded by open ocean, Scott Reef is bathed in nutrient-poor oceanic waters that lack the inputs from river systems or human activities which affect many other reefs.

On the broadest scale, the dominant oceanographic feature in the region around the reef is the Indonesian Throughflow. This critical part of the global ocean circulation transports warm, nutrient-poor water from the Pacific Ocean, through passages between the islands of Indonesia and Timor-Leste, eventually depositing it into the eastern Indian Ocean.

The Indonesian Throughflow contributes to global climate cycles by transporting and redistributing heat between the Pacific and Indian Oceans. These currents are highly variable over the span of months, years and decades, with the largest variations linked to the El Niño Southern Oscillation phenomenon.

The aquatic environment around Scott Reef has been the focus of research for almost 20 years. In 2008, that long-term research was expanded in an intensive two-year project to gain a more thorough understanding of how the reef's physical setting affects its biological communities.

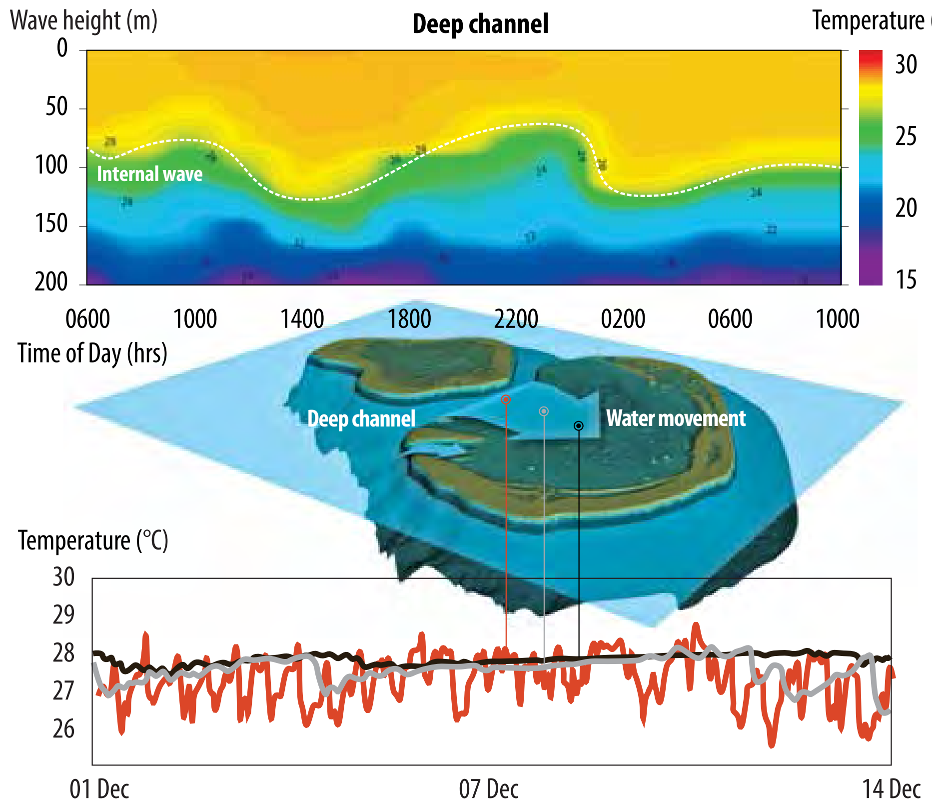
During this study, scientists sampled more than 40 monitoring stations around the reef and deployed a large array of water quality loggers and current meters. These instruments recorded conditions in the South Reef lagoon and deep channel continuously between March 2008 and February 2010, stopping only for retrieval and data download. Additional data characterising seasonal variation in oceanographic conditions around Scott Reef were collected during multiple surveys.



The Scott Reef system rises from the deep ocean near the edge of the continental shelf, and is far from the influence of mainland Australia. The Indonesian Throughflow dominates the supply of water to Scott Reef and its surrounds.

This vast amount of data confirmed that the ocean around Scott Reef, like much of the Timor Sea and eastern Indian Ocean, is characterised by two distinct layers of water. From the ocean surface down to approximately 100 metres is a well-mixed layer of warm, clear water, deficient in nutrients. Below this surface layer is cool water, richer in nutrients but less illuminated because of its depth. At depths of 400 metres, there is no light and the temperature can drop below 10 degrees Celsius.

The stable layering of the ocean around Scott Reef supports the existence of massive internal waves – waves within the water column, undetectable from the surface – which increase in size when they encounter the submerged reefs and banks in the area. These internal waves can reach heights of up to 110 metres, high enough to bring water up through the deep channel between North and South Reef and into the lagoon of South Reef. Driven by tidal forces, these intrusions typically occur twice a day, and bring vital nutrients into the shallow reef areas, increasing the productivity in the water column.



Huge internal waves moving through the deep ocean reach 110 metres in height as they encounter Scott Reef. The internal waves – waves within the water column – force cool, nutrient rich waters from the deep up through the channel and into the South Reef lagoon.

South Reef lagoon – warm and clear

The main focus of recent oceanographic studies was the deep lagoon, which reaches depths of up to 70 metres, within the large (400 square kilometres) horseshoe-shaped South Reef. Because of its shape, the South Reef lagoon is open to the surrounding ocean via the deep channel to its north. The water here is warmest in April and coolest in late August, with daily averages ranging from 25 to 31 degrees Celsius. Water quality loggers showed that the twice-daily incursion of deep water through the channel contributes to large daily temperature fluctuations of up to four degrees Celsius.

The oceanographic studies also quantified the clarity of the waters in the South Reef lagoon. Within the water column in the central area of the south lagoon there is very little suspended matter, with nearly undetectable concentrations. Consequently, light can penetrate to depths of more than 50 metres. This clear water and available light is crucial to the plant and animal communities in the South Reef lagoon, enabling them to survive in far greater depths than on other reefs with lower water clarity.

North Reef lagoon – warmer and cloudier?

North Reef has a shallower and more enclosed lagoon than South Reef, never exceeding 20 metres depth, with only two small channels linking it to the surrounding ocean. The oceanography of the North Reef lagoon has not been well studied, but given its shape, researchers expect its water column to be warmer and more turbid than the South Reef lagoon. Considering there is limited scope for flushing, residence times in the north lagoon are long and in sunny periods the water is more likely to become warmer and saltier due to evaporation. During times of extreme rainfall it can also become less saline than the surrounding ocean. Tidal currents are weak, and sediments include a combination of coarse sand and fine silt. This fine silt is resuspended when strong winds blow over the shallow lagoon and light penetration may, therefore, be more variable than in the South Reef lagoon.

Plankton soup

Around the globe, oceans are filled with small drifting plants, animals, viruses and bacteria known collectively as plankton. The oceanographic study of the plankton around Scott Reef uncovered an abundance of previously undescribed biodiversity.

Within the animal plankton (zooplankton), researchers found more than 260 different species in samples taken around the reef, many of which had never been identified before. A detailed taxonomic study of the group known as copepods found more than 220 species. Almost one-third of these species were new records for Australian waters and at least 14 appear to be previously unknown. Perhaps even more remarkable was the biodiversity within just one family of copepods, the Oncaeidae, which alone comprised more than 65 species.

Even more abundant than the zooplankton in the waters around Scott Reef were the minute photosynthesising plankton (phytoplankton) they feed on. Researchers found that more than 70 per cent of these were less than two microns in size – about one-fiftieth the width of a human hair. The phytoplankton samples were dominated by the marine bacteria *Prochlorococcus* and *Synechococcus* – these bacteria are among the most abundant photosynthesising organisms on the planet.

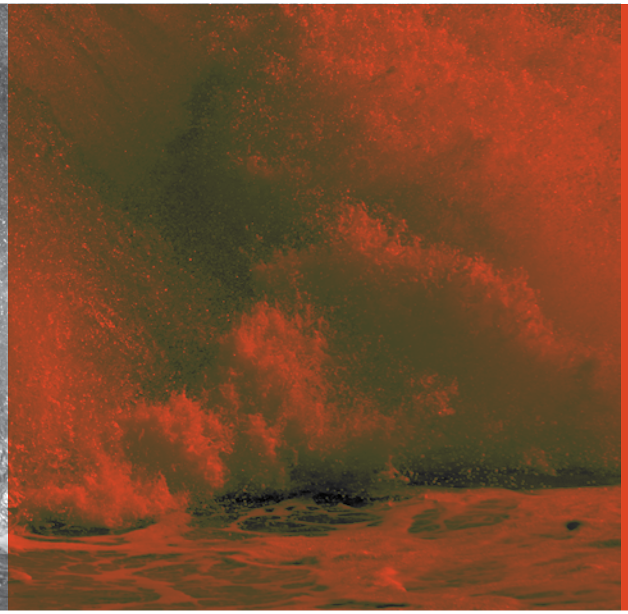
Each day, the phytoplankton populations around Scott Reef rise and fall in numbers. During the day, when sunlight is available for photosynthesis, the cells rapidly divide and multiply. At night, numbers dwindle as they are consumed by grazing zooplankton or destroyed by viral infections. These viruses are the most plentiful 'living' organisms within the Scott Reef lagoon and surrounding waters. Each millilitre of water can contain up to 10 million viruses, which mainly infect bacteria such as the *Prochlorococcus* and *Synechococcus*.

The rate at which phytoplankton are killed by viruses and grazing zooplankton is so high that communities of photosynthesising plankton in the waters around Scott Reef are born and die within a single day. This means that nearly all the organic material produced by these organisms is recycled within the water column, and very little sinks down to filter-feeding communities living on the sea floor below. As a result, the deep water corals in the South Reef lagoon obtain most of their nutrition from the photosynthetic algae that live within their tissues and not by feeding on other organisms or organic material.

This in turn means that the high water quality of the reef is of critical importance to the health of these deep water coral communities. In fact, the highly transparent, nutrient poor waters that bathe Scott Reef are well suited for the development of coral reefs. This is reflected in the remarkable biological diversity of the reef system, which includes almost 500 species of fish and more than 300 species of coral.

Instrument arrays were deployed into deep water and retrieved several months later for cleaning, servicing and data download. The instruments gathered data about the surrounding waters, including temperature, current speed and turbidity, to help further understand how the physical environment at Scott Reef influences its biological communities.

In the detailed study of zooplankton at Scott Reef, at least 14 species of copepods found were previously unknown to science.



Disturbances

Tropical cyclones occasionally bring destructive wind and waves to Scott Reef. Cyclone Fay passed over the reef in 2004, causing widespread damage.

Since it was first formed, Scott Reef and its ecosystem have been altered significantly by changes in global climate and ocean level occurring over millions of years. Over time-frames more relevant to humans, other events have also regularly affected the reef and its communities. Occasional cyclones, extreme tides, outbreaks of coral predators and diseases are part of the dynamics at Scott Reef. However, these disturbances are increasingly compounded by human impacts, a situation that threatens coral reefs around the world. Researchers have documented a range of disturbances at Scott Reef since monitoring began in 1994. Their challenge is to understand which of these disturbances – in isolation and in combination – pose the greatest threat to Scott Reef, and whether the reef is likely to be resilient to the more severe regimes of disturbance predicted in the future.

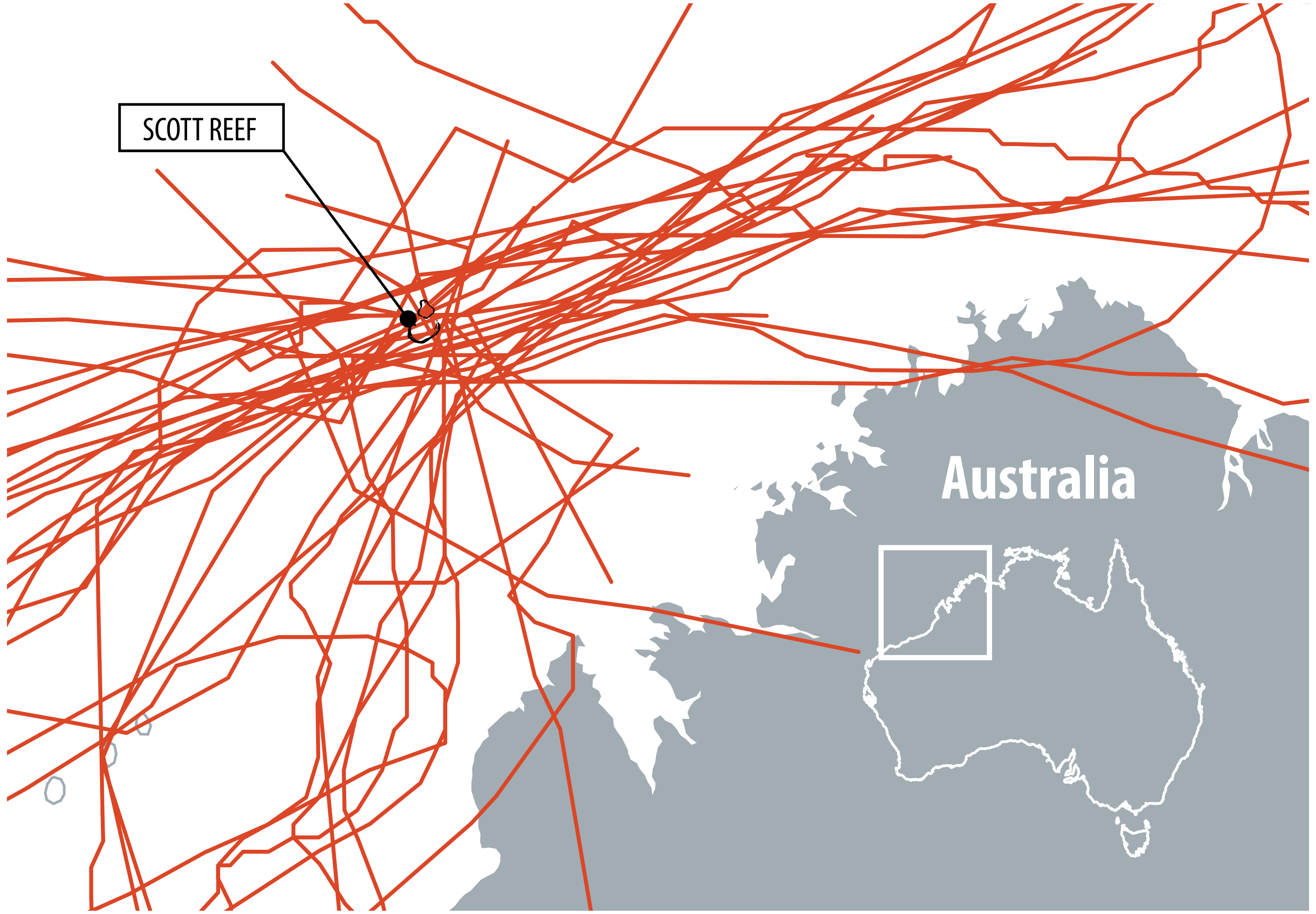
Historic disturbance regimes

Coral reefs are considered to be resilient to a range of natural disturbances. In part, this is because these disturbances occur only periodically, allowing the reef a chance to recover in the meantime. This resilience also stems from the fact that natural disturbances often have patchy effects – different communities or groups of corals are affected to varying degrees and even a severe event may leave some areas relatively unharmed. When disturbances only affect certain corals and leave survivors, recovery can be quick. The survivors can regrow and produce new offspring, and recovery will be further aided by an influx of coral larvae from nearby areas that were not badly affected.

Tropical storms and cyclones

Most coral reefs exist in shallow water in tropical climates. Consequently, the disturbances they often encounter include severe storms and cyclones. Powerful swells and waves can smash coral colonies into pieces and bury them under sediment and rubble, and torrential rainfall and freshwater runoff lead to deadly reductions in salinity. However, the impacts from most storms and cyclones are relatively minor, and in some instances the disturbance can actually increase diversity by removing some corals that would outcompete others if left unchecked.

Scott Reef is no stranger to cyclonic disturbances. Indeed, it has been severely damaged by a cyclone every few decades, and moderately impacted every few years.



Cyclones often pass in the vicinity of Scott Reef, but direct hits from severe storms are less common. In the past hundred years, more than 30 cyclones have passed within 50 kilometres of the reef.

When category 5 cyclone Fay tracked directly across Scott Reef in 2004, its 300 kilometre per hour winds caused widespread damage. The damage was most severe along the exposed side of the reef, where thousands of coral outcrops, some several metres in diameter, were dislodged and pushed up onto the reef flat. Studying the reef soon after the storm, researchers found that branching corals at shallow sites were either completely removed or smashed, leaving only stumps.

The damage was not restricted to branching corals. Soft corals and massive corals were also torn from their bases or broken into pieces. There was evidence of such damage down to 20 metres depth, and corals that escaped wave damage were buried under sediment and fragments of other coral colonies.

Cyclones as severe as Fay have been rare at Scott Reef. A storm of this magnitude may only affect the reef every 100 years or so, but in the past two decades others have also caused less severe harm to the coral communities. For example, cyclone George in 2007 damaged many fragile corals in some of the shallow communities at less than five metres depth.

Cyclone Fay generated powerful waves that caused extensive damage at Scott Reef in 2004. On the exposed parts of the reef, boulders up to several metres across were pushed up onto the reef flat, and even the most robust corals were broken into pieces or buried under rubble.

Coral diseases and predators

Periodic outbreaks of coral diseases and predators may well have affected reefs for thousands of years and, like storms, could also serve to regulate the abundance of a few dominant species. However, large and frequent outbreaks have only been documented more recently – when human activities have disrupted the natural balance of reef ecosystems.

There are about 30 known coral diseases, caused by organisms such as bacteria and viruses. They can be passively dispersed through the water column or transmitted by other animals. With names such as black band, dark spots and white syndrome, these diseases can be lethal to corals.

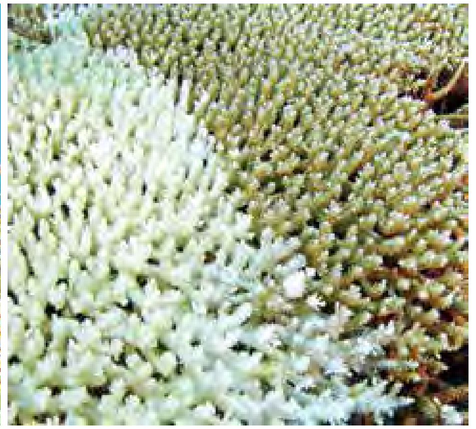
In contrast to the many different diseases affecting coral reefs, outbreaks of coral predators most commonly involve just two animals – the crown-of-thorns starfish *Acanthaster planci* and the marine snail *Drupella*. These predators feed on live coral tissue, leaving behind scars of exposed white coral skeleton.

Many reefs throughout the Caribbean and Indo-Pacific have been severely impacted by outbreaks of coral diseases and predators. Periodic outbreaks of the crown-of-thorns starfish have also severely affected parts of the Great Barrier Reef, as has *Drupella* at Ningaloo Reef in Western Australia. The reasons for these outbreaks are not known, but some theories attribute outbreaks to human activities, such as a higher survival of larvae in areas of poor water quality and high nutrient run off, or a reduced abundance of the organisms that naturally feed on these coral predators.

At Scott Reef, coral diseases and predators are constantly present, but usually in very low abundance. An exception was a recent outbreak of disease in 2010, which primarily affected table corals at a few communities. This outbreak was probably 'white syndrome', which is caused by the bacterium *Vibrio coralliilyticus*. Investigators know that low water circulation, turbidity, high water temperatures and a high cover of susceptible corals can trigger an outbreak of white syndrome. These conditions were present at the few parts of the reef worst-affected by the disease outbreak.

Since 1994, researchers have observed crown-of-thorns and *Drupella* occasionally at Scott Reef, but never in the high densities characteristic of outbreaks. When these predators were observed, they were usually feeding opportunistically on colonies that had already been injured by some other disturbance, such as a cyclone, disease or bleaching.





Periodic outbreaks of coral predators and diseases may have been part of Scott Reef's history, but they have been rare since research began at the reef. The coral-eating snail *Drupella* (left), crown-of-thorns starfish *Acanthaster planci* (centre), and the coral disease 'white syndrome' (right), can all be found on the reef, but are generally uncommon. An exception was a recent disease outbreak that affected some table corals in 2010.

Contemporary disturbance regimes

In addition to existing disturbances that have shaped the evolution of coral reefs, disturbances associated with human activities are now becoming more frequent and severe. The ultimate cause of these threats is overpopulation and overexploitation of resources. Approximately 850 million people – one-eighth of the world's population – live within 100 kilometres of a coral reef. And by 2015, around half of the world's population will live near the coast, which will only increase pressure on marine ecosystems.

Fifty years ago, coral reefs appeared resilient, able to recover from even large disturbances. However, the growing number and severity of disturbances mean that coral reefs today often face cumulative impacts. When several disturbances occur together or in quick succession, the reef's ability to recover will be diminished.

Local, regional and global phenomena all affect reefs. For example, the local degradation of water quality due to overfishing and increased input of sediments and pollutants can occur alongside the regional effects of high seawater temperatures that lead to coral bleaching.

There is also serious concern that human activities are increasing the frequency or severity of some disturbances. Elevated water temperatures may increase the likelihood of disease outbreaks or the severity of cyclones, nutrients may increase outbreaks of crown-of-thorns starfish, and overfishing increases the proliferation of algae.

Collectively, a combination of disturbances has dire consequences for coral reefs – one-fifth of the coral reefs around the world have already been severely damaged and 35 per cent are predicted to be lost in the next few decades unless impacts are reduced. Apart from the irreplaceable natural wealth that is lost, this has important implications for the sources of food and income that coral reefs provide to humans – a contribution which during 2010 alone was estimated at tens of billions of dollars.

The benefits of isolation

Given the role of human overpopulation in the degradation of coral reefs, not all reefs are on the same trajectory. Indeed, those far from the mainland, including Scott Reef, often escape exposure to the degraded water quality or overfishing that affects inshore reefs.

Coral reefs are generally found in nutrient-poor waters, and an increase in nutrient levels can result in algal blooms that effectively smother corals, particularly when numbers of herbivorous fish are low due to overfishing. Decreases in water clarity can reduce the light reaching the corals, and therefore the energy obtained through photosynthesis, and high levels of sedimentation can cover and injure coral tissue. Scientists have measured the water quality at Scott Reef, testing for levels of nutrients, turbidity and sedimentation. Results have shown extremely high water quality – probably a result of its distance from coastal river systems and human sources of nutrients and pollutants.

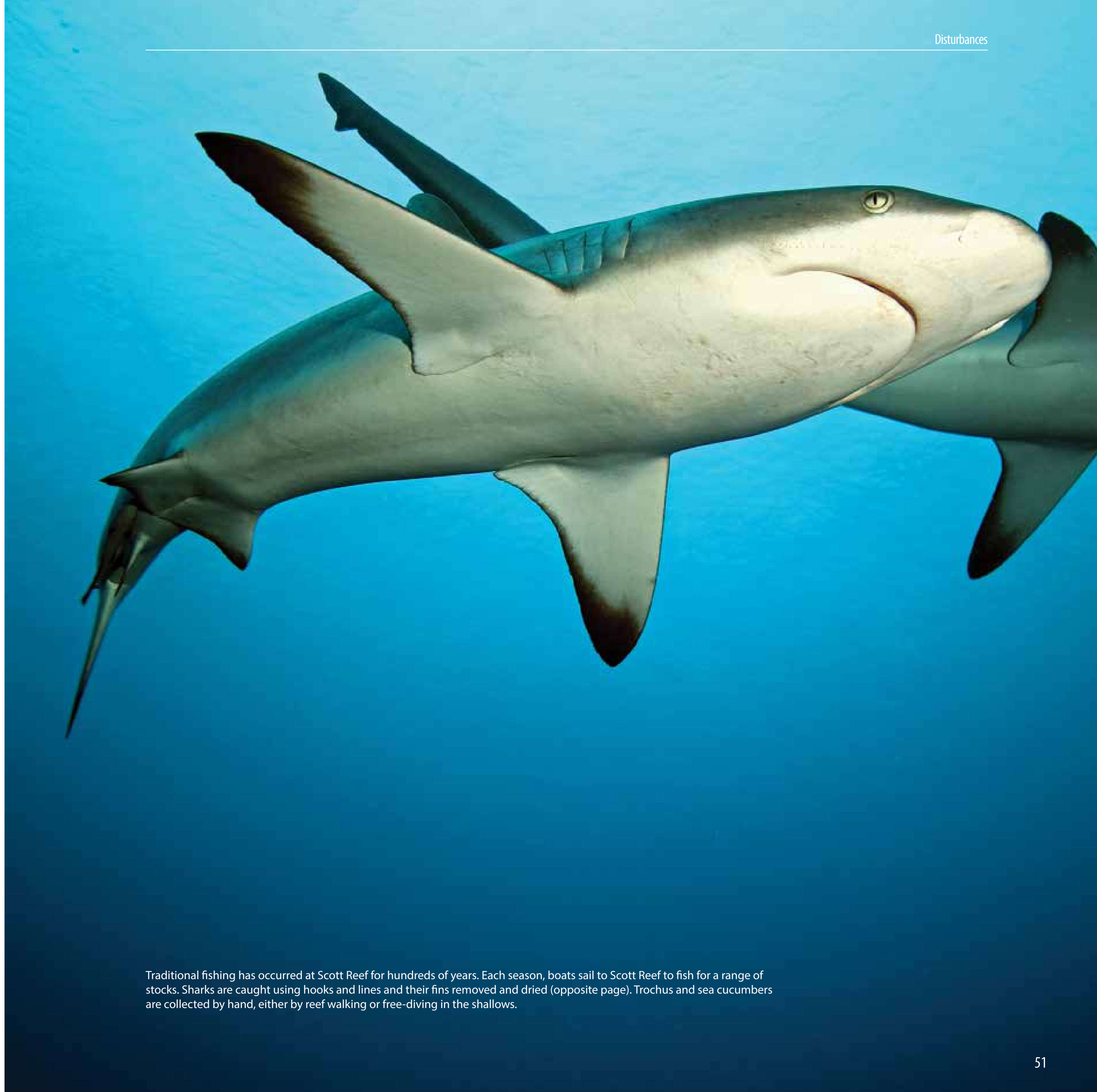
Similarly, herbivorous fishes are abundant at Scott Reef, and these play a critical role in controlling algae and maintaining space for coral recolonisation following disturbances. Maintaining this high water quality and the abundance of herbivorous fishes is vital for the ongoing health and resilience of Scott Reef.

Not isolated enough

The destruction caused by human activities is far-reaching, and even Scott Reef's isolation cannot protect it from some of the problems facing other reefs around the world.

Scott Reef is under little pressure from industrialised commercial fishing, but has been exposed to traditional fishing for more than 300 years. Fishing at Scott Reef continues in traditional wooden boats, from which sea cucumbers, trochus, reef fishes and sharks are collected. Although this has largely been restricted to a few target species, the pressure on these stocks is considerable and there is concern that additional species are now being targeted, and fishing methods are becoming more destructive. In recent years, around 80 fishing vessels have visited the reef each season, each with approximately 10 fishers on board. Compared to the other offshore reefs in the region where traditional fishing does not occur, there are far fewer sea cucumbers, trochus and sharks at Scott Reef.

Although the fishing pressure at Scott Reef pales in comparison to the destructive practices occurring at many reefs around the world, the removal of target stocks is still likely to have altered the dynamics of the ecosystem. For example, the loss of sharks can affect the numbers of smaller predatory fish, with implications further down the food chain, where pressure on prey species is increased. Fishing has undoubtedly changed the reef ecosystem from a truly pristine state, but for now it has not directly affected the coral communities at Scott Reef.



Traditional fishing has occurred at Scott Reef for hundreds of years. Each season, boats sail to Scott Reef to fish for a range of stocks. Sharks are caught using hooks and lines and their fins removed and dried (opposite page). Trochus and sea cucumbers are collected by hand, either by reef walking or free-diving in the shallows.

Our changing climate

The isolation of Scott Reef is also not enough to protect it from the global consequences of modern human activities. One of the greatest threats to coral reefs around the world is coral bleaching caused by the elevated sea-water temperatures that accompany climate change. There are few places where this has been more evident than at Scott Reef.

The potentially devastating phenomenon of mass bleaching occurs when higher water temperatures, or sometimes other physical stresses, disrupt the relationship between reef-building corals and the symbiotic algae that live within their tissues. Through photosynthesis, these algae provide the coral with oxygen, glucose, glycerol and amino acids – vital energy the corals use to survive, grow and reproduce. As well as supplying nutrients, the algae also give corals their remarkable range of colours.

Increases in water temperature can cause corals and other organisms to expel their symbiotic algae, leaving them pale or bony white, and without a key source of energy. This is a critical situation for the coral – if temperatures subsequently drop, these corals may recover. If not, they will perish.

Scientists have known about coral bleaching for decades, but the implications for coral reefs in the face of a changing climate have only recently been realised. During the summer of 1997 and 1998, reefs in every region of the world were devastated by elevated water temperatures and mass bleaching. Around 16 per cent of the reefs died, with those in the Indian Ocean being among the worst affected.

At Scott Reef, temperatures rose above normal in February 1998 and remained high for two months. Corals in all habitats down to 30 metres depth, across the entire reef system, bleached and died, reducing coral cover by around 80 per cent. The destruction caused by the mass bleaching is still evident at Scott Reef more than a decade later, and some coral and fish communities have still not fully recovered.

Repeated bleaching events have become a feature of some coral reefs, and a second, less severe, bleaching event impacted Scott Reef following elevated water temperatures in 2010. In contrast to the mass bleaching in 1998, the more recent event affected only a few locations and types of corals. Nevertheless, the latter event highlights the reef's susceptibility to climate change.

Future disturbance regimes

Although Scott Reef is free of many of the disturbances affecting other coral reefs around the world, in almost two decades of monitoring it has been exposed to a catastrophic mass bleaching event and several other disturbances. These subsequent disturbances were far less severe, but their cumulative effect slowed the recovery of the Scott Reef system following the mass bleaching.

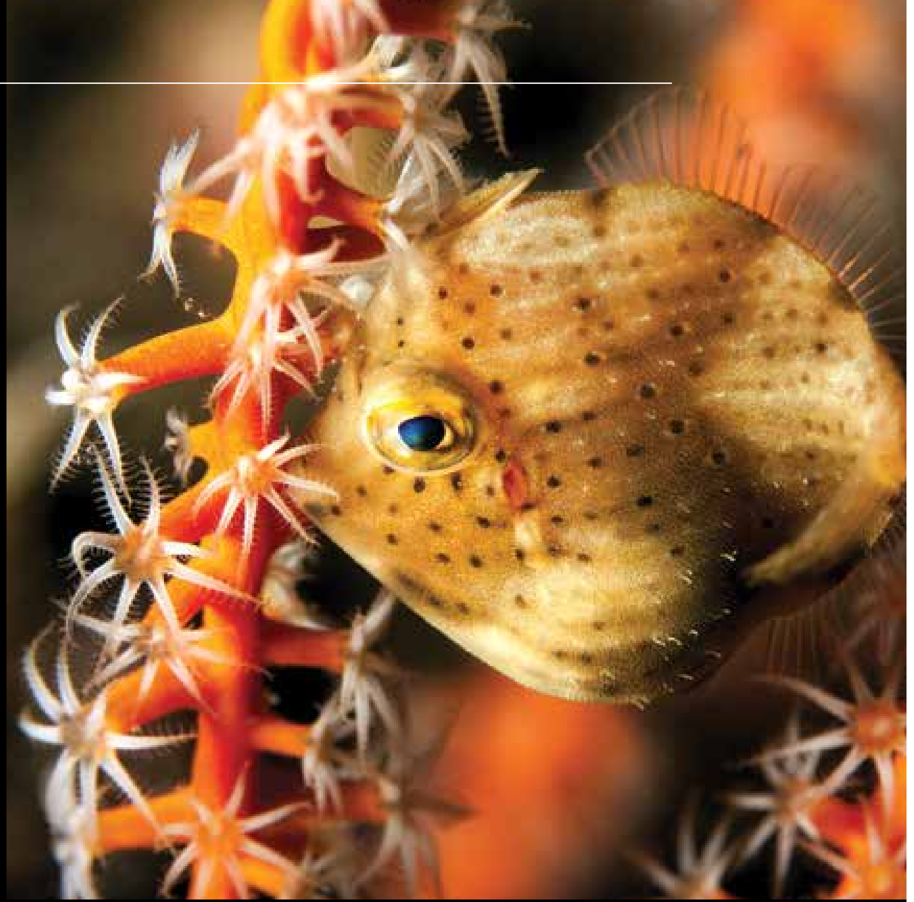
Consequently, the coral communities remained in a relatively degraded state for almost a decade after the mass bleaching, and any additional disturbances would have further slowed the rate of recovery. Indeed, for the communities at Scott Reef to remain in a healthy state will require a disturbance regime less severe than that seen in the previous decade.

As concentrations of atmospheric greenhouse gases rise, many scientists predict that climate change will continue to compound natural regimes of disturbance, and may introduce entirely new disturbances of unknown significance, such as ocean acidification – which potentially weakens the skeletons of marine organisms, including corals. How Scott Reef will respond to its changing regime of disturbance in the coming decades is unknown, but will be a major focus of future research efforts.

Although bleaching in hard corals is often the most conspicuous, in fact all organisms that contain symbiotic algae within their tissues may bleach when stressed. In an anemone, the symbiotic algae provide much of the organism's colour, so the loss of the algae during bleaching means the anemone becomes white or translucent.

BIOLOGICAL COMMUNITIES

Biodiversity



Coral reefs contain a phenomenal diversity of organisms that are linked together in complex ways. Reefs with high biodiversity may be better able to adapt to changes in their environment, and may contain undiscovered resources.

From its wave-battered outer walls and sunny reef top, to the calm waters of its deep lagoon, Scott Reef is home to a vivid array of life. Surveying the reef, researchers have identified thousands of different species – glittering reef fish, multitudes of shrimp, snails and sea stars, sea urchins and seaweeds – each living within an ecosystem built by corals over hundreds of thousands of years. In turn, these crowds of smaller organisms attract larger animals such as sharks, whales, dolphins, turtles and seabirds.

Like all coral reefs, Scott Reef is an oasis of biodiversity in a vast, relatively unproductive ocean, offering a bountiful supply of food and shelter. Among the most diverse ecosystems on the planet, reefs are home to a quarter of all marine species. The location of Scott Reef adds another dimension to its biodiversity. Its formation near the edge of Australia's continental shelf and unique deep lagoon lend distinctiveness to the biological communities found at the reef.

Diversity and abundance

Biodiversity – the variety of life on Earth – is one of the wonders of our planet. Around the world, millions of different types of organisms inhabit a wide range of ecosystems. This diversity not only creates a beautiful environment, it is functional as well. In a biologically diverse, healthy ecosystem, everything is in balance. Species are inextricably linked and their interactions produce food, shelter and competition, all of which are necessary to maintain the balance and preserve life.

Ecosystems with a wide range of species have a greater capacity to adapt to environmental changes. That diversity also makes them critically important to humans, by harbouring the potential for undiscovered resources, such as medicinal compounds.

At Scott Reef, divers swimming through the clear waters of the shallows, or the deeper blue regions where the exposed edge of the reef drops away into the dark, are surrounded by a remarkable abundance of life. Rays of sunlight illuminate bright red sea fans, schools of darting blue and yellow reef fish, sea snakes, anemones and more. Surveys at Scott Reef have so far identified more than 1200 species of animals and 120 different algae, including more than two dozen species not yet identified anywhere else in Western Australia.

Guard crabs (*Trapezia* spp.) make their home among coral branches, where they are protected from predators. In return, the crab will fight off coral predators, such as the crown-of-thorns starfish. This relationship is just one example of the unexpected ways in which organisms interact to maintain coral reefs.

Reef builders

Scott Reef is made up of the skeletons of countless reef-building organisms that have accumulated over millions of years. Corals and coralline algae contribute their limestone skeletons to the solid reef matrix that forms the platform for the multitude of other species on the reef.

Ultimately, these reef-builders are responsible for harbouring the biodiversity of the entire ecosystem at Scott Reef. Corals are the primary source of food or shelter for many of the organisms on the reef, such as hundreds of species of fishes, crustaceans and echinoderms – many organisms make their homes by boring directly into the coral's skeleton, including sponges, molluscs and worms.

The corals on a reef also contribute indirectly to the lives of a much larger range of organisms – sometimes in hidden ways. For example, the surfaces of dead coral skeletons provide an ideal place for algae and sponges to attach and grow. These algae and sponges are then fed upon by fish and molluscs. When the coral dies, its skeleton will eventually crumble and become part of the sediment that sea slugs, snails and starfish feed upon, and that worms and crustaceans live within.

Many reef organisms that benefit from corals also contribute to the wellbeing of the reef in ways that we are only beginning to understand. Herbivorous fish consume the algae growing on the skeletons of dead corals, preventing it from proliferating and overgrowing live corals. Tiny crabs that live among coral branches fight off crown-of-thorns starfish that attempt to eat their host. The crustose coralline algae that grow over coral skeletons are in turn a favourite settlement surface for coral larvae, which then grow into adult corals. These complex interactions contribute to the cycle of life and death that maintains the ecosystem and its biodiversity.

Organisms not only find shelter among corals, but also within them. Christmas tree worms (a type of polychaete worm) create a burrow inside the coral's skeleton, into which they quickly retract if threatened.

From the largest to the smallest, a huge variety of marine life can be found at Scott Reef. The largest animals, like the whale shark (above), are typically rare – while smaller creatures, including tiny sea squirts growing in colonies (opposite page), are found in far greater numbers.

Creatures large and small

Generally speaking, scientists have found that the diversity of Earth's ecosystems, Scott Reef included, can be thought of as taking the shape of a pyramid. At the base of the pyramid are large numbers of smaller species of plants, animals and other living things. As the organisms become larger toward the top of the pyramid, there tend to be fewer species, and fewer individuals of each species.

At Scott Reef, smaller species have populations numbering in the thousands, or more, but usually have very short life spans. Less abundant but equally important are the large animals, which may live for decades, or even centuries.

Although most sponges and corals are smaller and shorter-lived, some can grow to sizes of several metres across and live to be hundreds of years old. However, the turtles, dolphins, whale sharks and whales remain the largest animals found at Scott Reef.

Measuring diversity

To measure the diversity of life on the reef, researchers begin by dividing it into distinct habitats. At the simplest level, the reef can be divided into the protected waters inside the lagoons, the exposed reef flat on top of the barrier wall of the atoll, and the outside, exposed edge of the reef. But within each of these zones there are more subtle divisions based on physical characteristics, such as the depth of the water, whether the sea floor is made up of sand or rock, and so on.

Taking samples of the marine life from different reef zones allows researchers to build up a picture of overall diversity and abundance, and to find patterns in distribution. Perhaps the richest diversity at Scott Reef is found in the lagoon of South Reef. In particular, the transition zone between the reef flat and the deep lagoon offers protected waters and a variety of habitats that are home to an amazing array of species.

So far, studies at the reef have produced some impressive numbers. The diversity at the reef includes at least 300 scleractinian coral species in shallow water habitats alone, from almost 60 genera and 14 different families. When researchers surveyed Scott Reef, Seringapatam Reef and Mermaid Reef (Rowley Shoals) they recorded a total of 118 species of crustaceans, 339 molluscs, 52 echinoderms, 132 sponges, 461 fishes and six sea snakes. These surveys showed that some species were unique to only one of the reefs, including 79 of the 132 species of sponge. Not surprisingly, the measure of a reef's biodiversity depends on how much time scientists spend looking, and there are probably many unnamed species still to be discovered at Scott Reef, as well as at its neighbouring reef systems, where additional surveys are still required.

Life at Scott Reef does not end at the ocean floor. Living within the soft sand and sediment of the seafloor around the reef is a host of invertebrate organisms. In 2009, researchers surveyed the 'infauna' within the seafloor at 32 locations across the continental shelf, including deeper waters south and east of Scott Reef, and found 2250 different organisms. In some samples, there were up to 1800 individual organisms per square metre, although others contained far fewer. Overall, the most abundant animals were bristleworms, a class of worms found in oceans around the globe. Other animals included crabs and shrimps, ribbonworms, clams, sea urchins, snails, sea stars and flatworms.

As with many coral reefs, most biodiversity surveys at Scott Reef have been restricted to depths that are safe for diving, usually less than 15 metres, and some habitats and communities have not been surveyed extensively. There is undoubtedly a multitude of undescribed species at Scott Reef, particularly in the deeper-water habitats and in its unique southern lagoon, and the diversity of life at the reef is likely to be even richer than current estimates suggest.

The wider context

With the data that have been gathered so far, researchers estimate that Scott Reef sits in the middle of the biodiversity spectrum for coral reefs. It currently has a similar number of coral species to its neighbouring reefs in the region, but fewer than the 'Coral Triangle' – a centre of maximum marine biodiversity around Indonesia, Malaysia, the Philippines, Papua New Guinea and the Solomon Islands – where each ecological region has at least 500 coral species.

Generally speaking, overall biodiversity tends to decrease further away from the equator. Researchers have found that the distribution of species at Scott Reef is more closely related to the fauna of Indo-Pacific clear water region than to the more turbid inshore Kimberley region, which reinforces the importance of water clarity to the ecosystem.

Habitats

Coral reefs can take many forms, from fringing reefs near the shore to more isolated atoll systems. Although there are many similarities between reefs at the broader level, each also has its own unique characteristics, including the mix of distinct habitats it provides. Describing these habitats is a first step to understanding the ecology of the reef, but when these habitats span hundreds of square kilometres, this is no simple task. At Scott Reef, technological developments over the past 20 years have been combined with more traditional approaches to help map habitats, and to understand the relationship between their physical conditions and biological communities. This approach has identified many habitats that are typical of oceanic reefs, but also revealed some that are unique to Scott Reef.

Home is where the habitat is

A habitat is a home for a community of organisms, with a range of physical conditions that best suit its inhabitants. It is these conditions and the most abundant organisms that researchers primarily use to distinguish between habitats.

In general, coral reefs are found in shallow, tropical waters, where temperatures are warm and there is plenty of light – the most conspicuous organisms are the hard corals that form the reef structure. Within a coral reef, however, smaller variations in physical and biological characteristics create many different habitats. The type of material that makes up the sea floor, levels of sedimentation, and exposure to waves all vary from one part of the reef to another, and are examples of factors that determine the types of corals, fishes and other organisms that live in a given habitat.

Communities of plants and animals are often best adapted to the specific conditions within different habitats. In deep waters, for example, only those species adapted to growing in low light conditions will survive. So deep water corals grow in a fragile spreading form that maximises light absorption. Conversely, in the shallows, corals are exposed to strong currents and waves, so a delicate skeleton may often be damaged, and is unnecessary, as light is readily available.

As well as being influenced by physical conditions, the species within a particular habitat are also affected by the dominant organisms. Some of the best-adapted, and therefore most abundant, organisms within a habitat facilitate the existence of others. The co-existence of corals and fishes is a prime example – the branching corals that characterise some reef habitats provide shelter for many small fishes, which in turn are a source of food for predators. So, when defining a habitat, it is important to first document the dominant organisms as these can provide valuable information about the wider biological community.

Broad habitat categories rarely reflect all the variation across a reef. The incredible diversity on a coral reef – both physically and biologically – means that there are in fact many different habitats that are rarely uniform throughout. With more detailed information, additional categories can be added to define habitat types at ever-finer scales. Eventually, however, these categories can become so specific that they are based on a single type of coral, or a particular species of algae, and their application to mapping large areas of the reef becomes logistically impractical. This poses a considerable challenge to researchers – at what level should habitats be distinguished, and how can they be most simply defined?

Describing habitats

Describing habitats is a painstaking task. Even the most basic habitat descriptions usually involve measuring many physical conditions, such as temperature, salinity, light, nutrients, turbidity, sedimentation, currents and wave energy; as well as a range of biological components, the abundance and diversity of many different groups of corals, algae and fishes must be described. The abundance estimates are important because they determine which organisms are most typical of the habitat and may be critical to its existence, while diversity estimates identify rare or endemic species.

Given the effort required to describe habitats in detail, researchers aim to identify a few components that can reliably predict the presence of others. For example, combinations of depth, light and seafloor might predict the most common types of corals – and in turn, certain assemblages of hard corals might predict the presence of algae, fish and other corals. The ability to use certain habitat features to predict others requires a good understanding of why organisms are found in different habitats, which comes from the detailed studies of their biology and ecology. This combination of information may ultimately enable entire reefs to be mapped by measuring a subset of predictive components.

The 'rugosity' of the seafloor – its texture and three-dimensional complexity – is an important predictive component used by scientists to determine the habitats found in that area. Sand, rock and different types of coral all vary in rugosity, and detailed mapping of the sea floor provides accurate predictions about the organisms present at any place on the reef.

At Scott Reef, researchers combined a range of techniques to create a picture of the reef's habitats. From a beginning with only basic knowledge of water depths, developments in technology are now helping scientists to predict habitat types more and more accurately.

Bathymetry

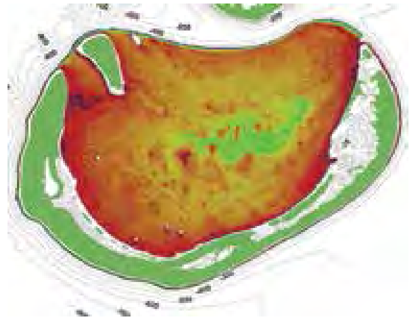
Measurements of the depth of water on and around coral reefs – known as bathymetry – have been collected for hundreds of years, and are among the most reliable predictors of habitat type. Variation in depth on a reef influences a range of other important physical conditions, such as temperature, light, currents and wave exposure, which in turn affect the biological communities.

Satellite photography

Satellite images were first produced in 1959 and today are available in very high resolution, showing features less than one metre in diameter. These images provide a more detailed representation of the structure of the reef, helping to distinguish the boundaries between some important physical and biological characteristics. For example, shallow patches of sand and coral outcrops can be distinguished throughout the shallow lagoon waters.

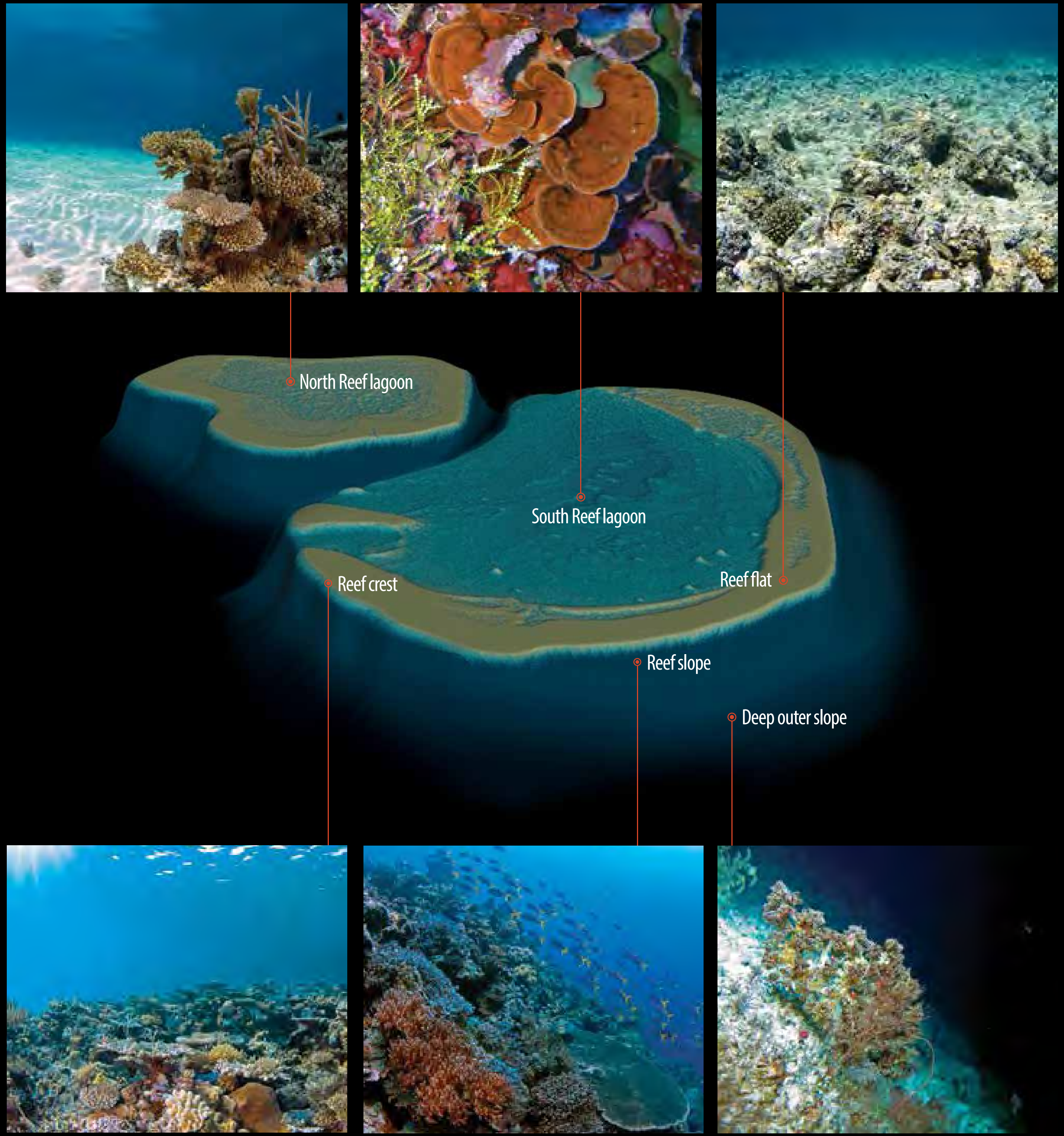
'Ground-truthing' habitat types

Once broad habitats are distinguished, their structure and biological communities must undergo ground-truthing – a process of verifying the classifications using a range of visual techniques. In 2006, researchers created a habitat map for Scott Reef by focusing on particular areas within general habitats. In the shallow waters, divers used photographs and video footage to describe in detail the type and structure of the seafloor, and the biological communities. Over larger distances and in deeper water, drop-cameras and towed-video were used to describe habitats. These data were then overlayed on to a map of existing physical data.



Predicting habitat types

In recent years, technological advances have greatly improved the ability to distinguish habitats over large areas by describing variation in a few important predictors. Technologies such as LiDAR (Light Detection and Ranging), which uses pulses of light, and multibeam sonar, which transmits a broad beam of acoustic signals, provide information about the communities on the seafloor. These data are compared to the detailed descriptions obtained in visual surveys, to determine their predictive capacity. Once refined, this approach may enable rapid habitat mapping over large areas, needing only a small area to be ground-truthed using detailed visual surveys.



Habitat divisions

Like most coral reefs, Scott Reef can be broadly divided into four main habitat types: the lagoon, reef flat, reef crest and reef slope. The lagoon is mostly enclosed by the reef and sheltered from large waves. The reef flat is the shallowest part of the reef structure, being exposed at low tide, and separates the lagoon from the reef slope. Where the reef flat reaches a peak and begins to slope away, it forms the reef crest. As this slope continues downward, the habitat continues to change – this area is referred to as the reef slope. Reef slopes form the edges of the entire reef structure and usually have the highest cover and diversity of corals. At Scott Reef, some of these general habitats are further distinguished by whether they are found in deep water, or located on the sheltered or exposed edges of the reef.

Reef flat

In the shallowest waters of Scott Reef, organisms living attached to the reef flat can be periodically exposed to the air, and more commonly endure high water temperatures and wave energy. Consequently, few corals survive in this habitat, and those that do are generally small and robust. In comparison to other habitats, there is generally a lower cover of corals on the reef flat and a comparatively higher cover of other organisms, such as algae and sea squirts.

Reef crest

The reef crest contains a combination of organisms found in the reef flat and reef slope. It can be the first point of contact for waves crashing onto the reef, and the corals have robust growth forms. Some tightly branching colonies are also found at the reef crest, but there are rarely large branching corals, whose growth forms are among the most vulnerable to wave energy.

Reef slope

As the reef slopes away into deeper waters, corals become more diverse and abundant. The ideal conditions for corals are found in the reef slope habitat, from a few metres down to approximately 20 metres depth. Here there is plenty of sunlight for photosynthesis and growth, while extremes in water temperature and wave energy generally do not penetrate below the first few metres. The cover and diversity of corals, fishes, sponges, algae, and many other coral reef organisms are often highest in this reef slope habitat.

The reef slope continues well below 20 metres, but around this depth there is a noticeable change in the biological communities that are present. Light becomes limited in the deep reef slope, so the cover and diversity of corals, and other organisms that rely on light, decreases. Indeed, the communities become sparser and there tends to be a higher concentration of organisms that obtain their nutrition by filtering particles out of the water, including sponges and sea whips.

Deep outer slope

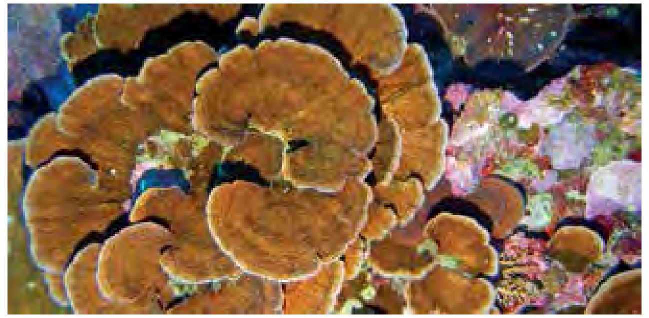
The outer slope of Scott Reef extends to depths of hundreds of metres. In depths of up to 300 metres, areas surrounding the reef continue to slope away, and present an entirely different habitat to the shallower areas of Scott Reef. Here, animals such as sea whips, worms, snails, sea stars and anemones live on, or burrow into, the sea bed.

Sheltered waters

Within a lagoon, the waters are calm and sheltered from the open ocean. But at Scott Reef, the shallow, enclosed waters of the North Reef lagoon contain a range of habitats that are very different to those seen in the deeper, more open lagoon of the South Reef.

North Reef lagoon

The lagoon inside North Reef has a maximum depth of 20 metres, but is generally much shallower. The plants and animals living within this habitat are sheltered from storms, but may be susceptible to the effects of high water temperatures. Little water is exchanged with the open ocean, which might also result in increased risk of disease outbreaks, particularly among corals.



South Reef lagoon

The deep lagoon within the horseshoe-shaped South Reef contains unique habitats. It covers approximately 280 square kilometres and provides corals with an entirely different set of physical variables than the shallow water environments. Corals in the deep water are less affected by temperature stress and wave energy, but they have very little light available for nutrition and growth – these communities are therefore far more susceptible to decreases in water clarity than those in the shallows.

Next steps

A phenomenal diversity of organisms live in each of the many habitats found at Scott Reef – from the worms and urchins found on the sandy seafloor in hundreds of metres of water, to sea squirts and algae that survive extreme temperatures, waves and periodic exposure on the reef flat. Each group of organisms is adapted to deal with the diverse conditions typical of each habitat. Among all these habitats, the shallow reef slope has the most abundant coral communities, but the habitats in the deep southern lagoon are unique.

After years of work, researchers now have a clear understanding of the different habitats at Scott Reef, and how physical and biological characteristics vary among them. Defining these communities has required considerable effort and utilised a range of different methods and technologies, and the knowledge gained from this research will make future efforts to map coral reef habitats far easier. The next step is to gain a better understanding of the characteristics that are most critical to the existence of each habitat, and how they can be used to predict the distribution of biological communities at Scott Reef and other reefs throughout the region.

Deep Water Communities

Scientists used ROVs to explore and sample the communities in the deep waters of South Reef's lagoon.

Of all Scott Reef's remarkable communities, perhaps the most intriguing are those that endure in the depths of its semi-enclosed south lagoon. Reaching depths of up to 70 metres, the sheltered expanse of crystal clear water in the lagoon at South Reef covers an area of more than 280 square kilometres. Historically, the sheer depth of these waters limited the amount of research that could be carried out in this part of the reef – much of it simply lay beyond the reach of researchers using SCUBA. In recent years, scientists have taken advantage of developments in remote technologies to survey these deep communities using cameras and remotely operated vehicles (ROVs). These studies have led to some remarkable discoveries about the extensive coral communities in the deep lagoon and how they adapt to living in the low light, low nutrient conditions.

A diverse ecosystem

When researchers sent cameras and ROVs into the depths of the South Reef lagoon they revealed a diverse community of hard and soft corals, sponges, algae, urchins and other organisms that covered much of the sea floor.

Down to depths of 60 metres, leaf-shaped foliaceous corals are the dominant growth form. Encrusting corals and branching *Acropora* corals are also widely distributed, albeit less densely than the foliaceous varieties, along with the bright green calcareous algae *Halimeda*, deep-red coralline algae, assorted sponges and high densities of soft corals, in different parts of the lagoon. Over 51 species of hard corals alone have been identified, many of which are also found in the shallows. However, in the shallows these species do not usually occur in high numbers, and often live in caves or under ledges, in low light and low current conditions similar to those in the depths.

Coral nutrition

Corals are unique among animals – reef-builders that gain much of their energy from sunlight. To obtain energy from light, corals host tiny, single-celled algae within their tissues, which contain light-harvesting pigments known as chlorophyll. These algae are from the genus *Symbiodinium* and they transfer the products of photosynthesis to their host, the coral.

In exchange for providing nutrition to the coral, the algae are provided a safe place to live and utilise the waste products of the corals for their own nutrition – this relationship is a true symbiosis that benefits both organisms. Maintaining this symbiosis is paramount to the health of the coral – if the environment changes and the algae are expelled, then the coral bleaches and may well die. The needs of the symbiotic algae often determine the ability of corals to withstand environmental stresses.

For reef-building corals to exist at a wide range of depths – from 0 to 100 metres – the symbiotic relationship must adapt to large differences in the amount of available light. Scientists have discovered different types of algae within a single species of coral, which may be important in allowing corals to live in diverse environments. Also, the number of algal cells, the amount of photosynthetic pigment in each cell, and the metabolic rate of the coral, can all be adapted to the different environments in deep and shallow waters. These adaptations may assist corals to live in a wide range of environmental conditions.

In the majority of cases, corals rely on sunlight for much of their nutrition. The symbiotic algae that live within their tissues use the light through photosynthesis to provide energy to the corals, in the form of carbohydrates. However, there is much less light available at the bottom of Scott Reef's lagoon than in shallower waters. Researchers calculated that just one per cent of the light available to support coral growth at the water's surface penetrates to the depths of the lagoon. How then are corals able to obtain enough food to build and sustain these abundant, diverse deep water communities?

Corals can also gain nutrition by feeding on particles they capture with their tentacles. For the majority of corals, this only makes a small contribution to their energy supply, but researchers hypothesised that given the lack of light, this type of feeding might be more important to the deep water corals. One theory held that nutrient-rich water entering the lagoon through the deep channel could cause plankton blooms, which would then sink to the deep water corals as a 'rain of food'. Yet investigations of this theory determined it was not the case. Most of the nutrients were rapidly cycled while still in the water column by tiny planktonic organisms, with very little reaching the lagoon floor to feed corals.

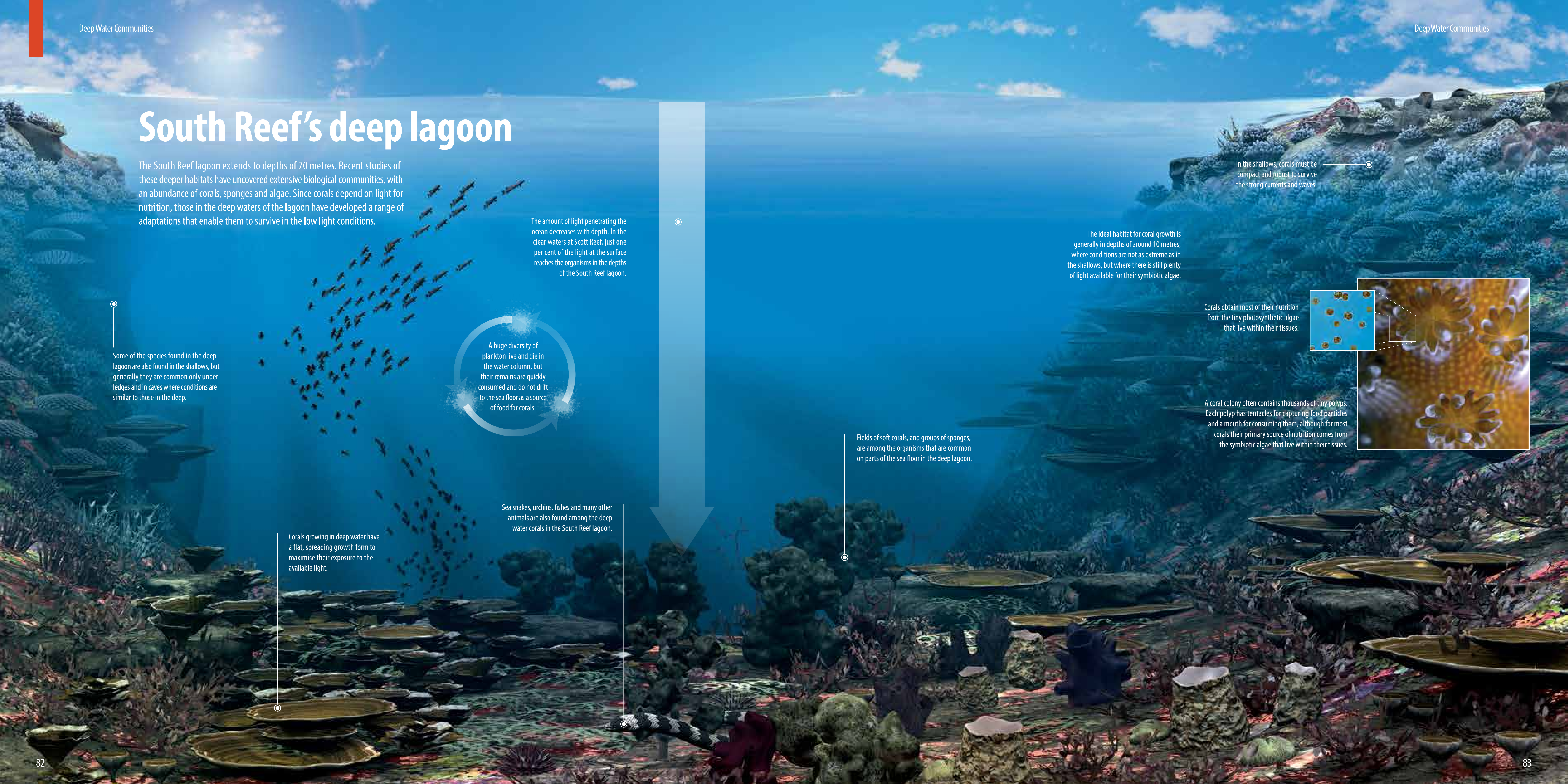
So, the deep corals must still rely on energy produced by photosynthesis within their symbiotic algae. Investigations then turned to other adaptations that allow the deep water corals to survive in the low light conditions available at these depths.


Researchers discovered extensive coral communities surviving to depths of 60 metres in the South Reef lagoon. The foliaceous corals were the most abundant, although corals with branching, massive or encrusting growth forms were also common. Regardless of their exact shape, all the corals growing in the depths had a spreading growth form that maximised their exposure to the available light.

Although corals typically receive much of their nutrition from the tiny symbiotic algae living within their tissues, they can also capture particles of food with their tentacles.

South Reef's deep lagoon

The South Reef lagoon extends to depths of 70 metres. Recent studies of these deeper habitats have uncovered extensive biological communities, with an abundance of corals, sponges and algae. Since corals depend on light for nutrition, those in the deep waters of the lagoon have developed a range of adaptations that enable them to survive in the low light conditions.



Adapted for the depths

After conducting detailed investigations into the physiology of corals living in deep water communities, researchers found evidence of multiple adaptations to the darker habitat – at a range of scales.

The most obvious adaptation is the flat, spreading growth form adopted by many of the deep corals, a shape that maximises the amount of the colony's surface exposed to light. In the shallows, strong waves or currents would easily break this delicate growth form, but in the deep these forces are far less powerful.

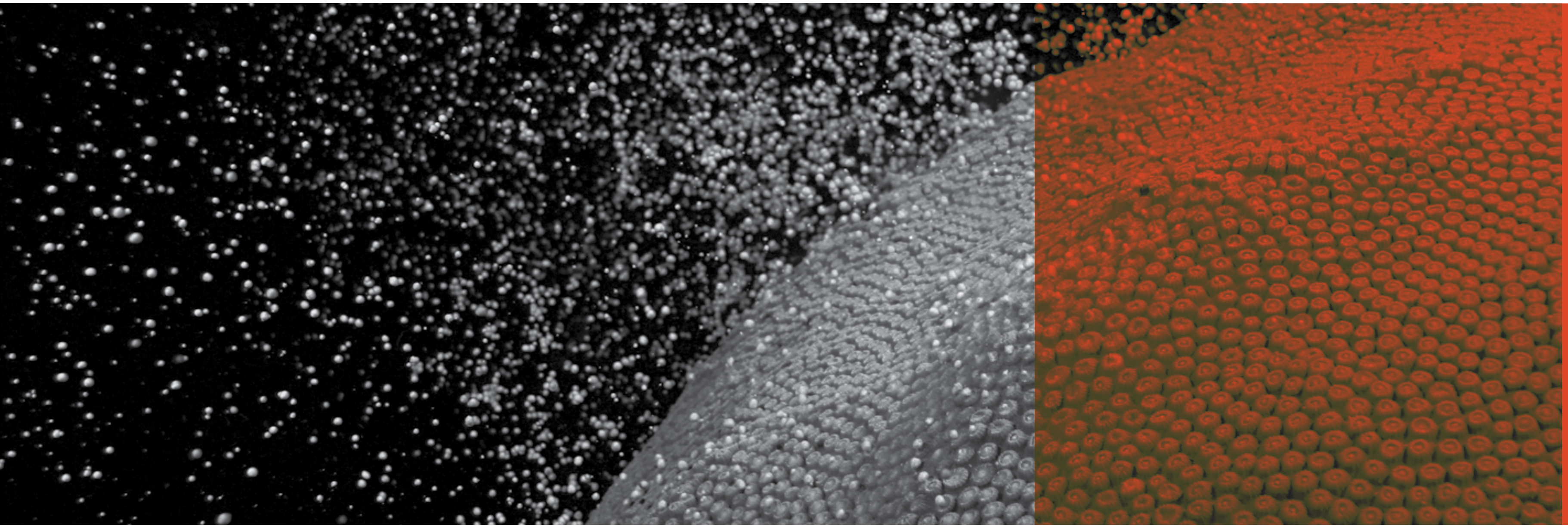
The other adaptations are less obvious and more complex. Within the colony, the mechanisms by which corals and their symbiotic algae harvest light and convert it to energy are also adapted to the deep environment. For some coral species, the types of algae change with depth, while in other instances the density and efficiency of the photosynthetic pigments within the algae are adapted to maximise energy provided to the coral.

In general, corals may possess efficient and flexible strategies that allow them to adapt to high or low light environments – strategies that are primarily based on their vital relationship with the tiny symbiotic algae that live within them.

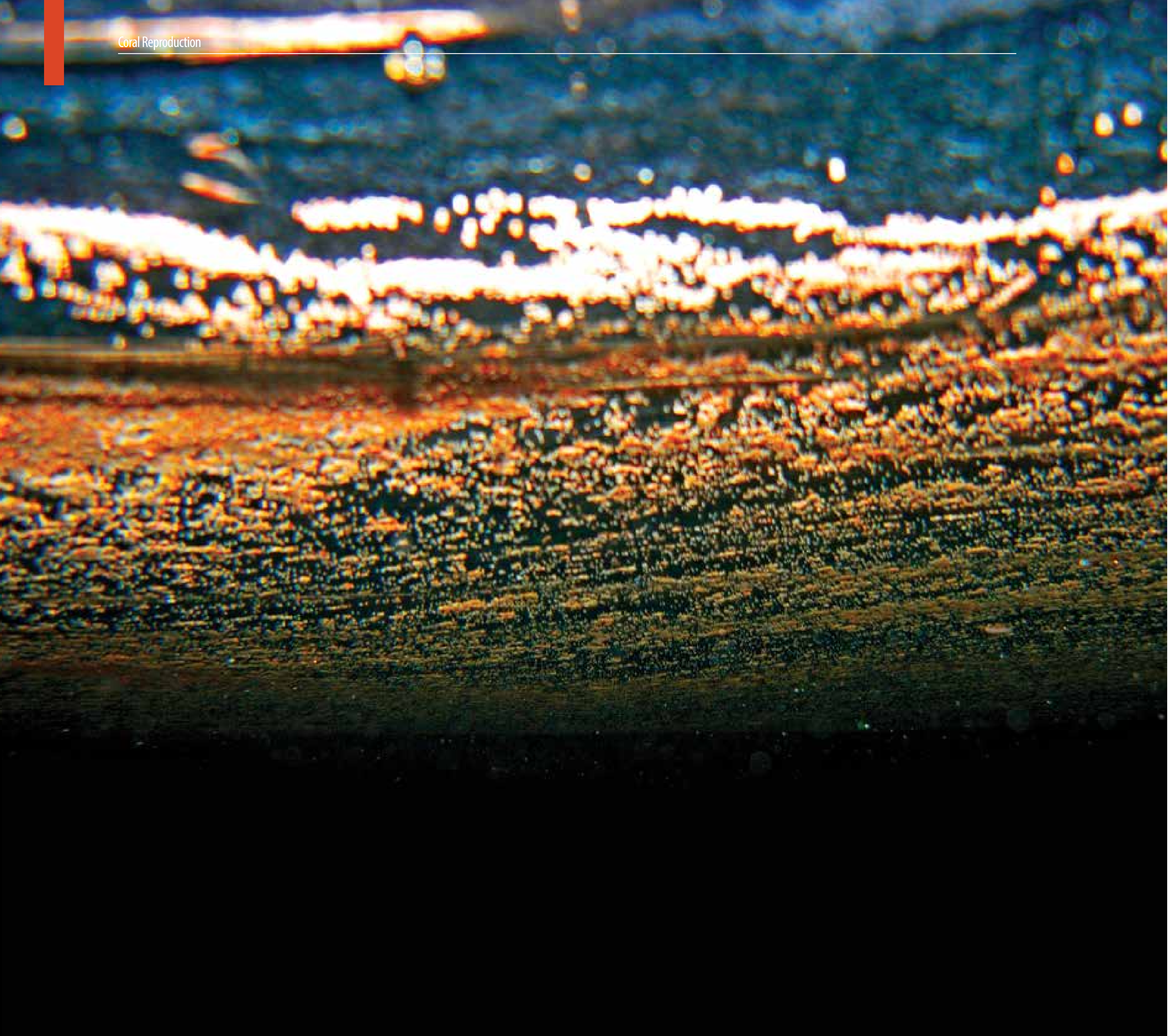
Even so, with increasing depth corals will eventually become limited by light. The deep corals in South Reef lagoon are near their limit of adaptability and any addition of suspended matter that further reduces light penetration may also reduce their growth and survival. As such, high water clarity is vital to the persistence of these unique communities.

Clear, clean water at Scott Reef allows light to penetrate to the deepest parts of the South Reef lagoon. This excellent water quality is critical to the survival of the unique, deep water coral communities.

CORAL ECOLOGY



Coral Reproduction



In mass coral spawning, many corals release eggs and sperm on a single night.
The eggs float to the ocean's surface and aggregate as huge slicks of coral spawn.

On a single night following a full moon in spring and autumn, the sperm and eggs of many thousands of corals fill the ocean surface around Scott Reef. These mass spawning events are a remarkable sight – the billions of eggs have been described as rising through the sea like champagne bubbles. The next day they can be seen on the ocean's surface as massive slicks of coral spawn. This spectacular mode of reproduction represents a crucial and potentially vulnerable moment in the lifecycle of corals. Detailed studies conducted by scientists working at Scott Reef have provided important information about coral reproduction and spawning that can help guide the management and conservation of the reef ecosystem.

A spring surprise

Thirty years ago, on the Great Barrier Reef, scientists first recorded the mass spawning of corals. This finding overturned a long-held belief that most coral species reproduced by fertilising eggs within their polyps, where the resulting larvae were brooded until they were ready to settle. In fact, it is now clear that around 80 per cent of coral species reproduce by broadcast spawning, where larvae develop in the water following the release of both eggs and sperm.

Following this discovery, mass coral spawning was also documented on some of Western Australia's most iconic reefs, including Ningaloo Reef and the Abrolhos Islands. But unlike the Great Barrier Reef, mass spawning on these west-coast reefs takes place in autumn, rather than spring.

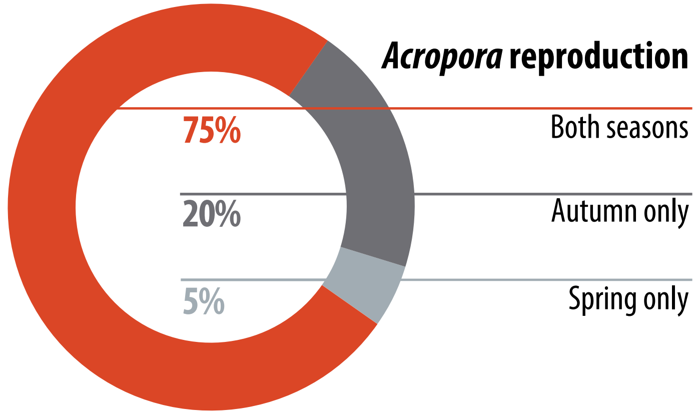
Later, in the 1990s, scientists working at Scott Reef and the Rowley Shoals confirmed that many coral species at these locations also spawned during autumn, in March or April, depending on the timing of the full moon. But further sampling in the 2000s turned up a surprise. In addition to the autumn mass spawning, a second, smaller spawning event was discovered in spring, usually in October, at a similar time to the events on the Great Barrier Reef. Since then, more than 75 species of corals have been sampled at Scott Reef, of which more than half have been documented to spawn in spring. However, very few of these species spawn only in spring, with most spawning during both seasons.

The most abundant species of corals at Scott Reef are in the genus *Acropora,* and it is their patterns of reproduction that are best understood. Of the *Acropora* studied so far, scientists have found that around 20 per cent of species reproduce only in autumn, another five per cent reproduce only in spring, while approximately 75 per cent do so in both seasons.

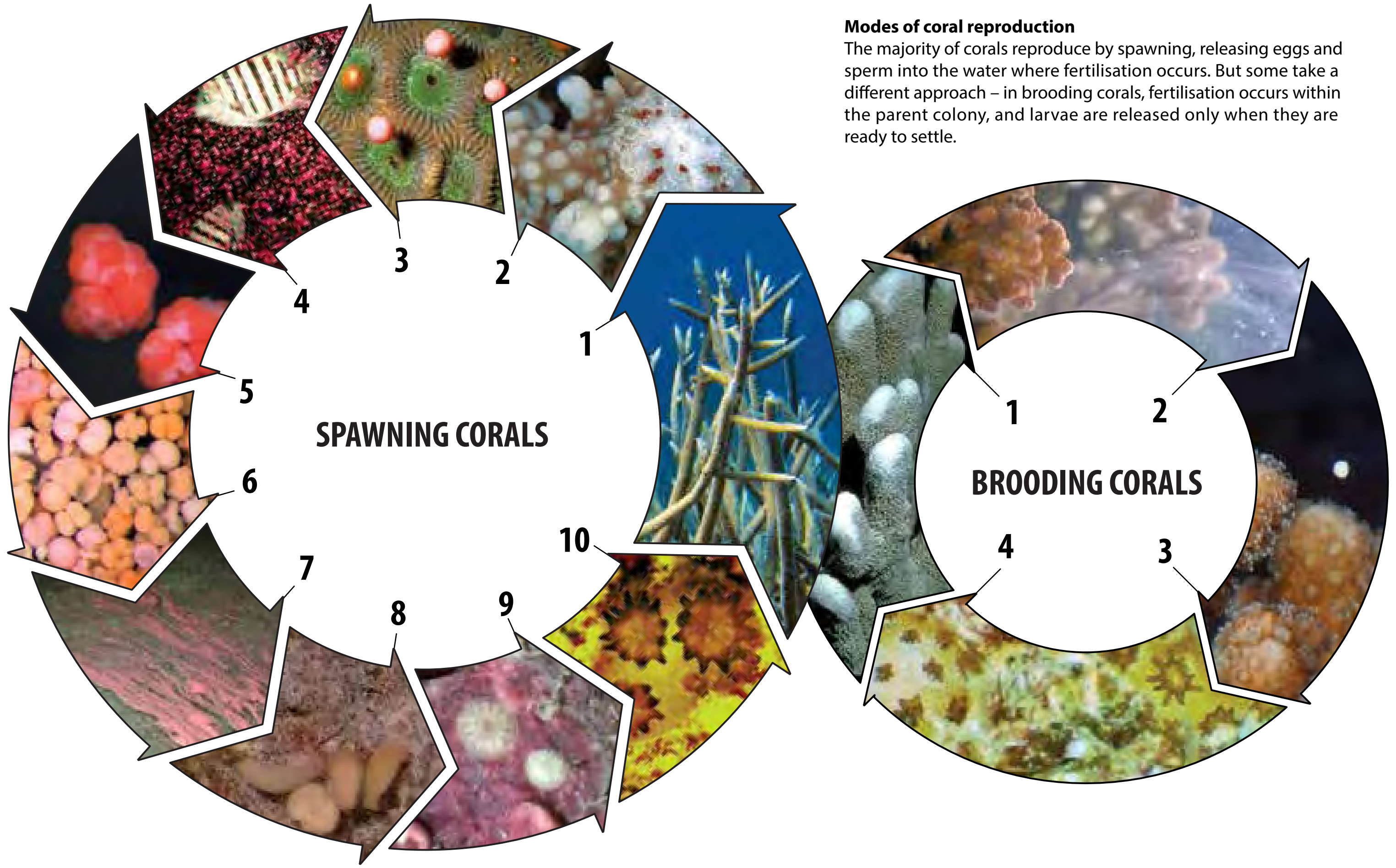
Spring spawning has since been documented on other Western Australian reefs north of Ningaloo, and the phenomenon of a primary and secondary spawning event has been documented at other reefs around the world.

The release of buoyant egg and sperm bundles from a colony's polyps at the time of mass spawning is one of nature's most spectacular events. Many colonies and species release eggs and sperm within a few hours of each other, with a range of other organisms also participating in the event.

The proportion of *Acropora*, the dominant group of corals at Scott Reef, participating in each of the two main seasons of spawning.



The *Acropora* are the most diverse and abundant corals at Scott Reef, and their many species have a wide range of shapes and colours. Most *Acropora* participate in the reef's mass spawning events in both autumn and spring, although a much larger proportion of colonies spawn in autumn.



Modes of coral reproduction
The majority of corals reproduce by spawning, releasing eggs and sperm into the water where fertilisation occurs. But some take a different approach – in brooding corals, fertilisation occurs within the parent colony, and larvae are released only when they are ready to settle.

Spawning corals

1. Maturity: Once a coral colony has reached a large enough size it becomes a reproductive adult.
2. Gamete development: Within the coral's many polyps, eggs develop over several months and sperm over several weeks.
3. Spawning: When fully developed, the eggs and sperm are released from the colony, often synchronously in spectacular mass spawning events.
4. Predation: Various predators feed on the rich feast of eggs and sperm.
5. Fertilisation: Many corals release their eggs and sperm in compact bundles, which float to the water's surface before separating. Amid this soup of gametes, fertilisation relies on sperm locating the eggs from another colony of the same species.
6. Cell division: Following fertilisation, eggs undergo a series of divisions through the different stages of embryogenesis before becoming larvae after approximately 24 hours.
7. Dispersal: Coral embryos and larvae form slicks on the water's surface. However, a day after spawning many of the viable larvae have already dispersed into the water column where they remain for at least two days before they are ready to settle. Some larvae may survive drifting in the water column for weeks before reaching a suitable reef habitat.
8. Settlement: Once ready to settle, and in the vicinity of a suitable patch of reef, larvae actively search the substrata for a site of attachment. The site they choose is critical, as they remain attached to this spot for life.
9. Metamorphosis: Once attached, larvae commence metamorphosis, taking on the characteristic form of a coral polyp.
10. Polyp budding: The coral polyp begins to excrete a calcium carbonate skeleton, and the colony grows through the repeated division of its polyps.

Brooding corals

1. Maturity and gamete development: As with spawning corals, the brooding corals must grow to a size at which they become reproductive adults. Many brooding corals tend to be either male or female, producing either eggs or sperm within their polyps, in contrast to spawning corals that are often hermaphroditic, producing both eggs and sperm within their polyps.
2. Fertilisation and larval development: Mature brooding corals release sperm into the water column, which reach another colony and fertilise the eggs within its polyps. The fertilised eggs develop into embryos and then larvae, and the larvae are then 'brooded' within the polyp for several weeks. This process may occur several times a year in brooding corals, whereas most spawning corals produce eggs and sperm only once each year.
3. Larval release: When developed, the brooded larvae are released by the polyps. Because most are ready to settle when released, the brooded larvae disperse over much shorter distances than the larvae of spawning corals that develop in the water column.
4. Settlement to polyp budding: As with the spawning corals, the larvae of the brooding corals attach to the substrata, undergo metamorphosis into a coral polyp, and then grow through polyp division.

What triggers mass spawning?

From an evolutionary perspective, mass spawning is thought to increase fertilisation success and reduce the likelihood of eggs being eaten when released, through 'predator saturation' – predators can only eat a small proportion of the billions of eggs released in one night. Exactly what environmental conditions trigger the timing of the mass spawning events remains uncertain. Changes in water temperature and the number of daylight hours are thought to influence the months in which gametes develop and mature. Within these months, the nights of spawning at Scott Reef typically occur following a full moon and during neap tides.

A complex interaction between evolutionary and contemporary environmental conditions evidently determine the number of corals and species participating in mass spawning events within a year. Research at Scott Reef has added detail to this understanding. Importantly, scientists have found that although many species of *Acropora* spawn during two seasons each year, individual colonies appear to participate in only one of the two events – over several years of sampling individual colonies, there was no evidence of them spawning twice a year or switching from one season of spawning to another.

Remarkably, even neighbouring colonies of the same species, experiencing the same environmental conditions, have been found to consistently spawn at different times of the year, suggesting it may be genetic differences that determine the time of spawning for a particular coral colony. Recent analyses have identified significant genetic differentiation between groups of colonies of the same species that spawn during the different seasons, far greater than the genetic differences between colonies on reefs separated by several hundred kilometres. These results raise the question of how often colonies of the same species, which reproduce during different seasons, interbreed.

At Scott Reef, adjacent corals of the same species (blue and green colonies, above), experiencing the same environmental conditions, consistently spawn during different seasons. Recent work suggests that genetic, rather than environmental, factors determine the season of spawning for coral colonies at Scott Reef.

Exceptions to the rule

Although most of the corals at Scott Reef spawn during one of two months, some abundant and functionally important corals reproduce at other times of the year and their cycles of reproduction are not well described. The massive *Porites* colonies that contribute significantly to the structure of Scott Reef spawn more than once throughout the year, as do the many colonies of *Pocillopora verrucosa*, although it remains unknown if individual colonies spawn more than once a year.

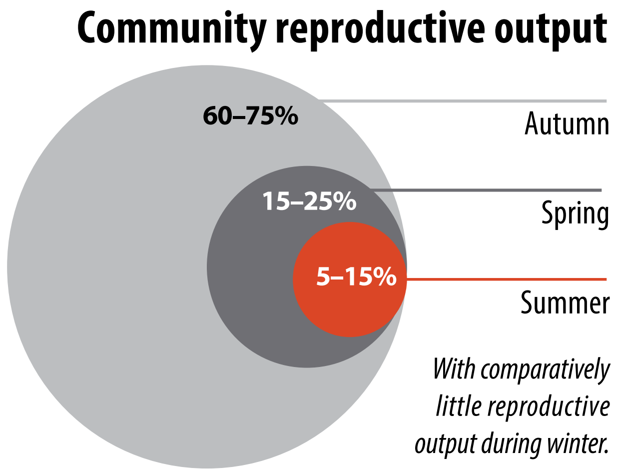
In contrast to the spawning corals, the many brooding corals at Scott Reef tend to have multiple cycles of reproduction throughout the year. Reproduction in brooding corals involves the release of sperm that fertilise the eggs within the polyps of another colony. Larvae then develop while still in the polyps and are released several weeks later, when they are ready to settle. Some brooding corals are particularly abundant at Scott Reef, including the extensive thickets of *Isopora brueggemanni*, or the finely-branching *Seriatopora hystrix*, and produce larvae over several months around the two mass spawning events in spring and autumn.

Some common and functionally important corals reproduce in ways different to most others at Scott Reef. The massive *Porites* (top left) and *Pocillopora verrucosa* (top right) release their eggs and sperm in many months of the year, not only during mass spawning events. The brooding corals *Seriatopora hystrix* (bottom left) and *Isopora brueggemanni* (bottom right) release larvae over several months of the year.

Conservation and management

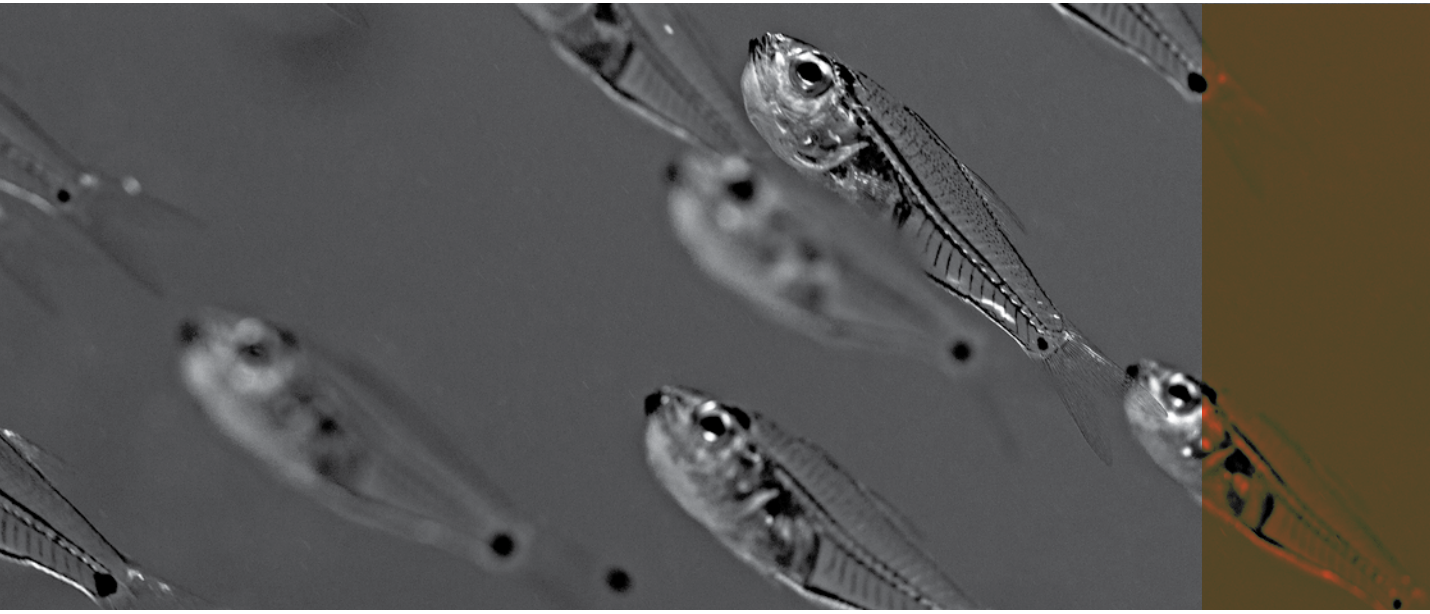
Detailed information about the patterns of sexual reproduction in corals at Scott Reef is important for their management and conservation. Sexual reproduction underpins the maintenance of coral communities and their recovery from disturbances, yet these early stages of the life cycle are particularly susceptible to environmental stresses.

However, simply counting the number of species that participate in a spawning event provides little information about how important its contribution is to community maintenance. Estimating the significance of reproductive periods during the year requires information on both reproduction and the abundance of species, but for many reefs this combination of data is remarkably rare. At Scott Reef, researchers have combined estimates of abundance with information about reproduction in spawning and brooding corals to assess which periods contribute most to reproductive output.



As expected, more than 60 per cent of the reproductive output for spawning corals occurred during autumn, compared to less than 30 per cent in spring. However, a larger proportion of reproductive output for a few species of spawning corals, such as the massive *Porites* or those spawning only in spring, occurred during months outside of autumn. Similarly, the reproductive output for most brooding corals was much lower in autumn than in all the other months combined. Considering the entire community of spawning and brooding corals, between 60 and 75 per cent produced larvae during autumn, between 15 and 25 per cent in spring and between five and 15 per cent in summer, with little evidence of larval production in winter months. These proportions vary between communities and from one year to another, depending on the timing of spawning events and the relative abundance of different species. Further work will provide more insight into the degree of spawning synchrony among species and colonies within these seasons and the reasons for the observed variation among years.

Understanding the modes and timing of larval production for corals at Scott Reef is important, as they influence the distance and direction of larval dispersal. As winds and currents at Scott Reef vary between months and seasons, the timing of reproduction can determine whether larvae remain on the reef, or leave Scott Reef and begin the long journey north or south to another reef system. The pattern of reproduction is the first factor influencing larval connectivity among coral reefs of the region.



Larval Connectivity

Scott Reef and its neighbours are separated by wide expanses of open ocean. Whether the reefs are connected by larvae regularly traversing these expanses, or not, has important consequences for the reefs' ability to recover from disturbances.

Scott Reef may be hundreds of kilometres from mainland Australia, but it is not entirely alone in the expanse of the Indian Ocean. Just 25 kilometres to the north is Seringapatam Reef, a close neighbour, while a few hundred kilometres away are Ashmore Reef to the north and the Rowley Shoals to the south. Understanding exactly how the communities of corals, fishes and other living things on these reef systems are connected has been an important puzzle for researchers. Are successive generations of organisms at Scott Reef only produced by local adults, or are some the products of neighbouring reef systems that have travelled as larvae through the open ocean? This question is difficult to answer, yet has critical implications for how reefs recover from damage, and how they should be managed.

A matter of survival

When faced with damage from coral bleaching, cyclones or other severe disturbances, do Scott Reef and the other oceanic reefs off Western Australia stand together, or alone?

If reefs are 'open', meaning they are connected reproductively to other reefs, then a supply of larvae from one may aid recovery from damage at another. If, on the other hand, they are 'closed' systems with little larval exchange, then recovery from a severe disturbance will depend only on local survivors.

Considering that more than 80 per cent of coral species are known to reproduce by broadcast spawning – sending billions of larvae out into the ocean where currents can carry them to new locations – it was once assumed that most coral reefs were open systems, routinely connected to other reef systems over distances of tens to hundreds of kilometres.

More recent research has altered this view. Scientists now realise that although coral larvae can survive to disperse through the ocean for several weeks, they are ready to settle within a week of spawning, and are likely to do so provided they are near suitable reef habitat. Additionally, the vagaries of the open ocean and the risks of predation mean many of the larvae that disperse for long periods may never survive to settle elsewhere. Consequently, most coral larvae settle far short of the maximum distance they are capable of travelling.

Unlike continuous reef systems such as the Great Barrier Reef, Scott Reef and its neighbouring reef systems are extremely isolated. For larvae originating from these reefs, travelling beyond the reef means crossing many kilometres of open ocean before reaching another reef. Their chances of surviving such a journey are very low.

Brooding fishes, such as the wolf cardinalfish (*Cheilodipterus artus*), protect their eggs from predation by carrying them in their mouths until they reach the larval stage.

Fish larvae are strong swimmers for their size, and are often found several kilometres from the reef in the open ocean where they grow, feed and develop until ready to settle.

Seringapatam Reef lies just 25 kilometres to the north of Scott Reef. The degree of larval exchange between these reefs is not known, but it is likely to be much higher for fish larvae than for corals, given their longer larval duration and superior swimming and sensory abilities.

After spending weeks in the water column, the fully developed larvae return to the reef to settle and become juveniles. Some fish larvae have excellent sensory abilities, and use ocean currents to assist their return.

Spawning fishes, such as the bicolour chromis (*Chromis margaritifer*), release eggs and sperm into the water column. The eggs are fertilised and the larvae develop while in open water, receiving no parental care.

Larval dispersal

Most corals and fishes undergo a larval stage, when they leave their parents and disperse through the water before settling at their new home. Understanding the distances and direction of larval dispersal is critical to managing coral reefs, but is extremely difficult to measure directly. Instead, scientists combine a variety of other information to determine the likely end points of the larvae's journey.

Spawning corals, such as *Acropora tenuis*, release eggs and sperm which are fertilised and develop in the water column. They spend days to weeks drifting with the currents until they are ready to settle, usually less than twenty kilometres from their parent colony.

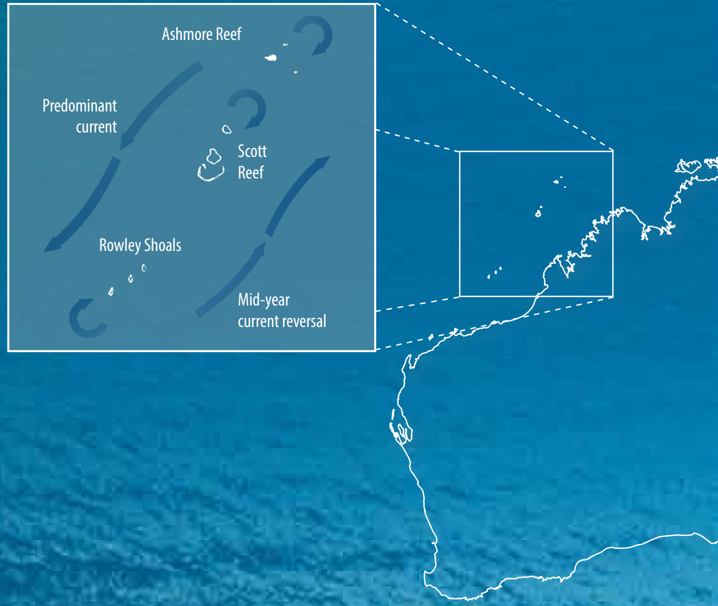
Most likely

Movements of larvae

Least likely

Brooding corals, such as *Seriatopora hystrix*, have eggs that are fertilised while still inside the parent's polyps. The resulting larvae are ready to settle when they are released. Most settle less than a few kilometres from their parent colony.

Scott Reef and its neighbours are extremely isolated. Moving between these reef systems is a long journey for both coral and fish larvae, which must travel for weeks on ocean currents over hundreds of kilometres. Scientists concluded that few larvae disperse successfully among these oceanic reef systems, with most settling on their home reef.



Going with the flow

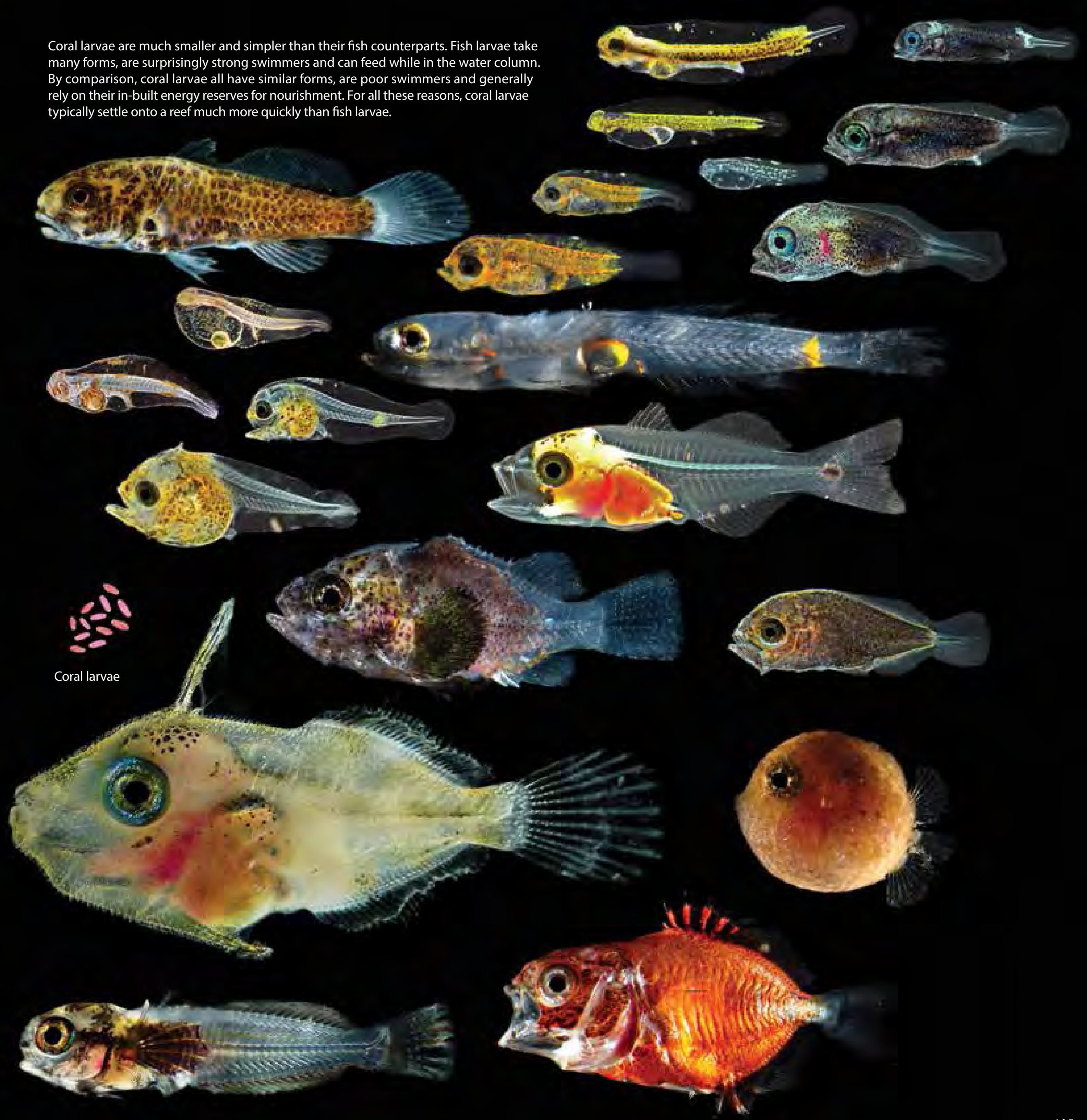
The likelihood of coral larvae from Scott Reef reaching one of the neighbouring reef systems depends upon the speed and direction of the currents in the surrounding oceans, and upon how long the larvae can survive before settling. Until recently, neither of these factors was well known.

To study the currents, scientists used satellite-tracked drifters, devices that they released from one reef system and tracked as they flowed towards other reef systems. In more recent years, they have also used ocean models to predict current movements over a much broader range of environmental conditions.

These studies have shown that during the calm conditions that characterise periods of coral spawning, prevailing currents can retain coral larvae within a reef system for days to weeks. Once in the open ocean, dispersal times between the reef systems are in the order of one to two months. Interestingly, in the middle of the year the currents switch direction, from a predominantly southward flow in autumn to a northward flow in spring.

Satellite-tracked drifters travel with slicks of coral spawn, documenting their movements. The path of the drifters is used as a proxy for the movement o f the tiny larvae.

Coral larvae are much smaller and simpler than their fish counterparts. Fish larvae take many forms, are surprisingly strong swimmers and can feed while in the water column. By comparison, coral larvae all have similar forms, are poor swimmers and generally rely on their in-built energy reserves for nourishment. For all these reasons, coral larvae typically settle onto a reef much more quickly than fish larvae.



The long journey

Once researchers had estimates of how long it might take coral and fish larvae to travel between reefs, they could contemplate the related question of whether larvae live long enough to make such a journey.

The larval competency period – the time taken before larvae are ready to settle – varies widely for different species. Among corals, most brooded larvae are ready to settle when released from the parent, and usually do so within hours. For spawning corals, which are the majority, larvae need at least a few days drifting in the water column before they are ready to attach themselves to the reef. This minimum competency period is also affected by the conditions in the water, such as its temperature, so can vary substantially between regions. To estimate natural rates of larval development at Scott Reef, scientists used nets to capture thousands of embryos and larvae following a spawning event in 2003, and simultaneously conducted settlement experiments in aquaria.

The results showed that coral larvae at Scott Reef were ready to settle and attach to the reef within three days of spawning, sooner than had been documented in earlier experiments at other reefs. This difference of just a few days can have important implications for the dispersal distances of larvae, particularly because it can mean the difference between remaining on the reef and being carried into the open ocean.

Fish larvae, unlike their coral counterparts, have longer dispersal times that can extend from weeks to months. They are also able to swim and sense the reef environment around them far better than coral larvae, meaning they have some control over the distance and direction that they travel, particularly when ready to settle. Fortunately for scientists, they also have an in-built recorder of the period they spend in the larval stage. To determine how long fish larvae remain in the water column, scientists analyse the fishes' ear bones, called 'otoliths'. These bones contain rings – similar to tree rings – that are laid down each day, and display a distinct signal when the larvae settle at their new patch of reef.

In 2010, researchers painstakingly measured increments on the tiny otoliths from hundreds of juveniles of two common fish species (*Chromis margaritifer* and *Cheilodipterus artus*) from Scott Reef. The results suggested that the larval fishes remained in the plankton for between 25 and 45 days before settling. Based on this planktonic larval duration and current speeds, they calculated that larvae could theoretically disperse between Scott Reef and the other reef systems.

As with the growth rings of a tree trunk, the ear bones (otoliths) of juvenile fishes record the time they have spent in the water column before settling on the reef. Each fine increment represents a day in their life, and these are counted up to the settlement mark, which is notably thicker.

Leaving home

Travelling through the open ocean is perilous for larvae. A huge variety of animals are eager to consume them, particularly as they approach a reef where the number of potential predators increases dramatically. Therefore, it is not enough to know that larvae theoretically could reach other reefs in the region, it is necessary to know whether they actually survive the journey in sufficient numbers to contribute to their new populations.

Directly tracking billions of tiny larvae through hundreds of kilometres of ocean to determine their destination is impossible, so researchers must infer this information from a range of indirect methods. In addition to the inferences based on current speeds and larval durations, the relationship between the number of adult individuals and the number of new coral recruits on a reef can also provide insights into larval connectivity.

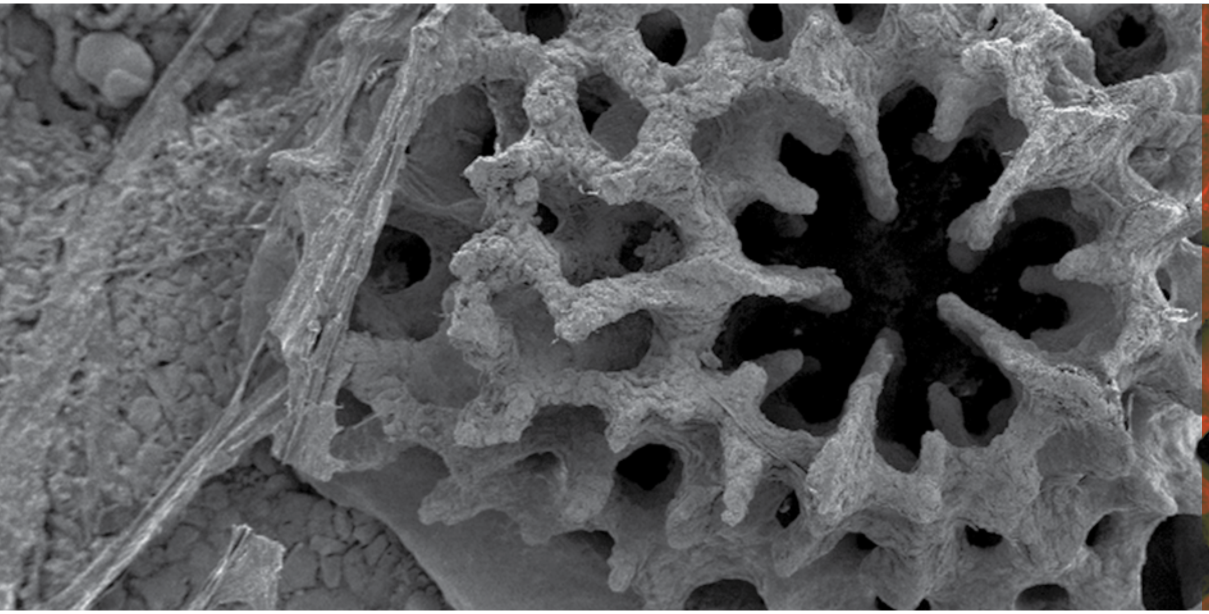
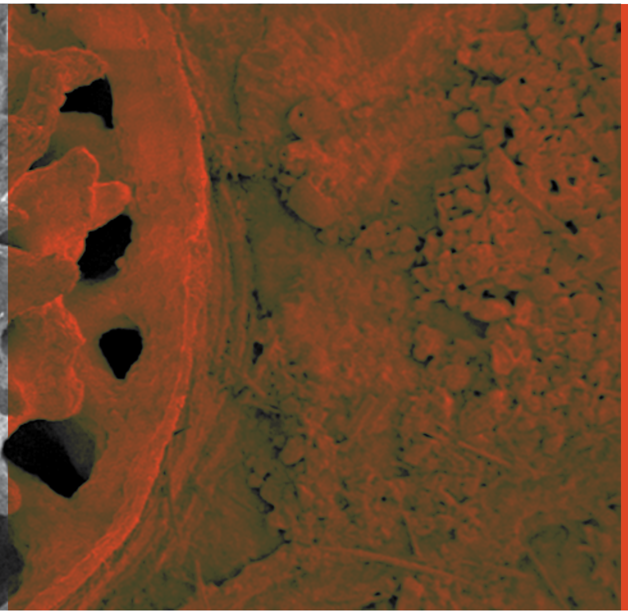
A powerful example of this approach emerged at Scott Reef, after the mass bleaching event in 1998 killed around 80 per cent of the corals. In the five years after the bleaching event, rates of coral recruitment were less than six per cent of those before the disturbance. However, over the following decade the number of new recruits increased proportionally to the number of adult corals, providing clear evidence that recovery depended on the survivors and was not aided by a supply of larvae from the neighbouring reef systems.

More recently, advances in genetic analyses have provided another way to examine larval connectivity among reef systems. In the first study of its kind in Western Australia, researchers examined the genetic identity of thousands of samples collected from two species of coral (*Acropora tenuis* and *Seriatopora hystrix)* and fish (*Chromis margaritifer* and *Cheilodipterus artus*). The genetic similarity among samples taken from different locations at Scott Reef and the Rowley Shoals allowed scientists to estimate larval connectivity within and among these reef systems. The results supported those obtained from the other methods, suggesting that the brooding coral typically disperses over distances of a few kilometres and the spawning coral over distances of less than 20 kilometres; as expected, the fishes dispersed over larger distances, typically among the reefs within each of the systems. However, there was little evidence of significant larval exchange between the two reef systems for either the corals or the fishes.

What's born on the reef, stays on the reef

Researchers at Scott Reef have taken a unique approach by combining a range of complementary methods to answer the complex question of larval connectivity. Combining oceanography with studies of larval development, stock-recruitment and genetics has led to the conclusion that the coral and fish communities at Scott Reef produce most of the larvae that replenish populations at this isolated location. There is little evidence of a large and regular supply of larvae from the other reef systems in the region.

In other words, when it comes to recovering from disturbances, Scott Reef and the other reef systems in the region are largely on their own. Without an external supply of recruits, communities may take longer to recover from severe, widespread disturbances than they would otherwise. Severe or repeated disturbances could also affect the persistence of susceptible species, potentially eradicating such populations from Scott Reef, with little hope for replenishment from external sources.

Coral Recruitment

After drifting in the water column, coral larvae attach themselves to the reef's surface and metamorphose into a single coral polyp. The new coral continues to divide and grow, competing for space against already-established organisms, including other corals, sponges and algae.

After drifting perilously through the water column, coral larvae face their next challenge – finding a suitable spot to attach to the reef, metamorphose, and grow into a young coral. No event in the lifetime of the coral will be more important than where it settles, as it will remain in that place for the rest of its life. This process – known as recruitment – is critical to maintaining populations by replacing the corals that have died. Researchers working at Scott Reef have long recognised the importance of this process to the reef, and in 1995 began one of the longest-running studies of coral recruitment on record. Tens of thousands of coral recruits have since been counted and identified, providing a unique insight into how recruitment varies according to the abundance of adult corals and the exposure of Scott Reef to varying disturbances.

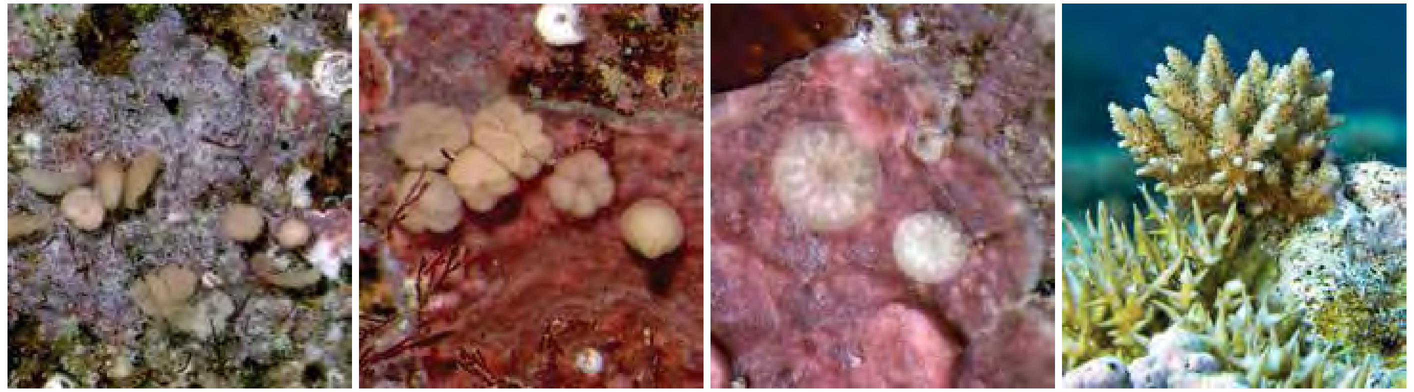
Settling down

Successful recruitment relies on the coral completing its larval stage, attaching to the reef and metamorphosing into a polyp, where it begins life as a coral colony.

Coral larvae are just one millimetre in length when they begin the process of settling. They can detect chemical cues that attract them to a patch of reef, and then spend some time searching the reef surface for a suitable site of attachment. Larvae most commonly attach to hard surfaces, coated in pink coralline algae and other microscopic biofilms, often showing preference for holes or crevices in the reef. The choice of settlement site at this early stage influences the survival of the coral through its entire life, as moving is not an option.

Once attached to the reef, a larva begins the process of metamorphosis. Within a day, it transforms from a sausage shape into a flattened disc, on which developing tentacles and a mouth are visible. Over the following days, the mouth and tentacles fully develop and the polyp secretes a calcium carbonate skeleton. This primary polyp divides to create another, these in turn divide, and the process continues, eventually producing a coral colony that may contain many thousands of polyps.

The tiny coral is particularly vulnerable in this early stage of its life. The colony is less than a few centimetres in size during its first year. At this age, it can easily be overgrown by other organisms, such as algae, sponges or even other corals. It can also be buried under sediment or rubble, or consumed by fishes scraping away at the reef while feeding.



Coral larvae respond to chemical cues while searching the reef surface. When selecting a suitable place to attach, they often prefer certain species of red coralline algae. After attaching, the larva metamorphoses and begin to form a mouth, tentacles and a skeleton. The single coral polyp then begins to divide, and the colony may eventually contain many thousands of polyps.

How many coral recruits?

Measuring coral recruitment provides important information about the health and resilience of a reef. High numbers of new coral recruits at a reef suggest it is receiving an adequate supply of coral larvae to sustain coral populations and predicts faster recovery from disturbances. In contrast, consistently low numbers of coral recruits suggest an unhealthy reef with coral communities that will decline in the future.

Counting the number of new corals on reef is, however, no easy task. Recruitment can be patchy and is influenced by a wide range of factors that researchers do not yet fully understand. For example, the number of new corals depends on the amount of available space – there may be more coral recruits on a patch of reef covered in coralline algae than on a patch densely covered by macroalgae, so estimates must account for these variables. Another challenge for scientists attempting to measure recruitment is the tiny size of the new corals – they are barely visible to the naked eye and can be extremely hard to find on the reef, especially given their preference for settling in small holes and crevices.

The researchers' solution to the problem of measuring coral recruitment is to provide the larvae with an alternative settlement surface, of a standard size and structure, that can be easily attached to the reef and then collected with the recruits attached. These 'settlement plates' are deployed approximately one month before coral spawning, during which time they become covered in the coralline algae and associated biofilms on which larvae prefer to settle. A month after spawning, the settlement plates are retrieved, and the tiny coral skeletons counted and identified under a microscope.

Opposite page: Researchers use settlement plates to measure the number of corals recruiting to a community. When first deployed, these terracotta plates are clean, but quickly become covered in the biofilms and the red coralline algae on which coral prefer to settle.

Recruitment in space and time

Across Scott Reef, scientists discovered that the number of coral recruits in shallow waters varied according to the number of adult corals – an extremely important finding that indicates recovery from disturbances at Scott Reef is not aided by a large supply of larvae from other reefs. This relationship was established after the 1998 mass bleaching event, when the number of recruits dropped to nearly zero following a comparable decline in adults. Monitoring over the following decade showed that the number of recruits remained low for several years, only returning to previous levels after the number of reproductive corals had also recovered.

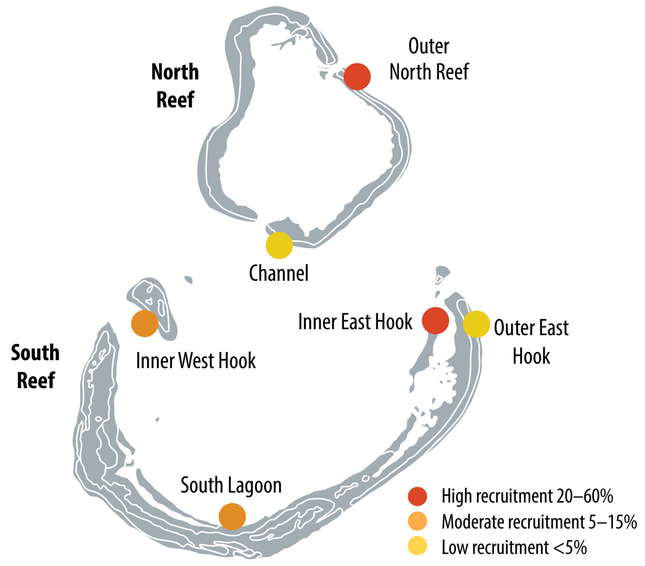
The relationship between the number of adults and recruits also applied to much smaller areas of the reef for the brooding corals. This is understandable because their larvae are fully developed when released and typically disperse over distances of less than a few kilometres – unlike spawning corals, whose larvae develop in the water column and can disperse over greater distances. Recruitment in the spawning corals varied considerably among locations, with certain areas showing either consistently high or low recruitment. This supports other research suggesting that the larvae of spawning corals can travel among locations separated by around 10 to 20 kilometres, and that the direction of dispersal is influenced by the prevailing currents. Thus, scientists were able to identify locations at Scott Reef that are sources, and sinks, of larval recruitment – information that is critical for managing the reef through disturbances.

Deep recruitment

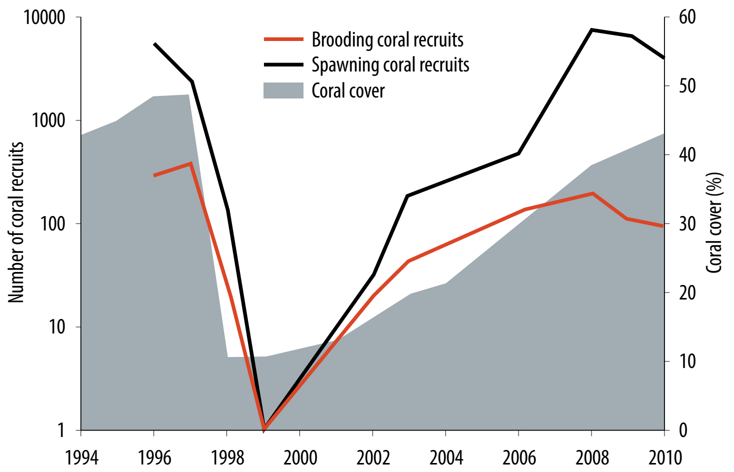
Much of the knowledge about coral recruitment at Scott Reef has come from the shallow reefs. However, the discovery of the extensive coral communities in the deep lagoon at South Reef led researchers to question whether reproduction and recruitment there display similar patterns to those seen in the shallows. Since divers cannot safely access the deep lagoon, settlement plates were attached to instrument frames lowered to the sea floor. Preliminary findings identified a peak in coral recruitment at the same time as the coral spawning in the shallows, suggesting similarities in reproduction between the shallow and deep water corals.

There were, however, some notable differences between the settlement plates deployed in the shallow and deep water. For example, recruits in the shallow water areas commonly settled on the underside of the tiles, whereas in the deep a much higher proportion settled on the upper surface, probably in response to the low light levels in the deep. Additionally, by far the highest number of recruits in the shallows belonged to a single coral genus, the *Acropora*. By comparison, there were far fewer *Acropora* recruits in the deep, which is reflected in the significantly lower adult numbers of these corals at these depths.

These initial findings provide some information about patterns of reproduction and recruitment in the deep water corals, but there is still much to learn about these newly discovered communities.

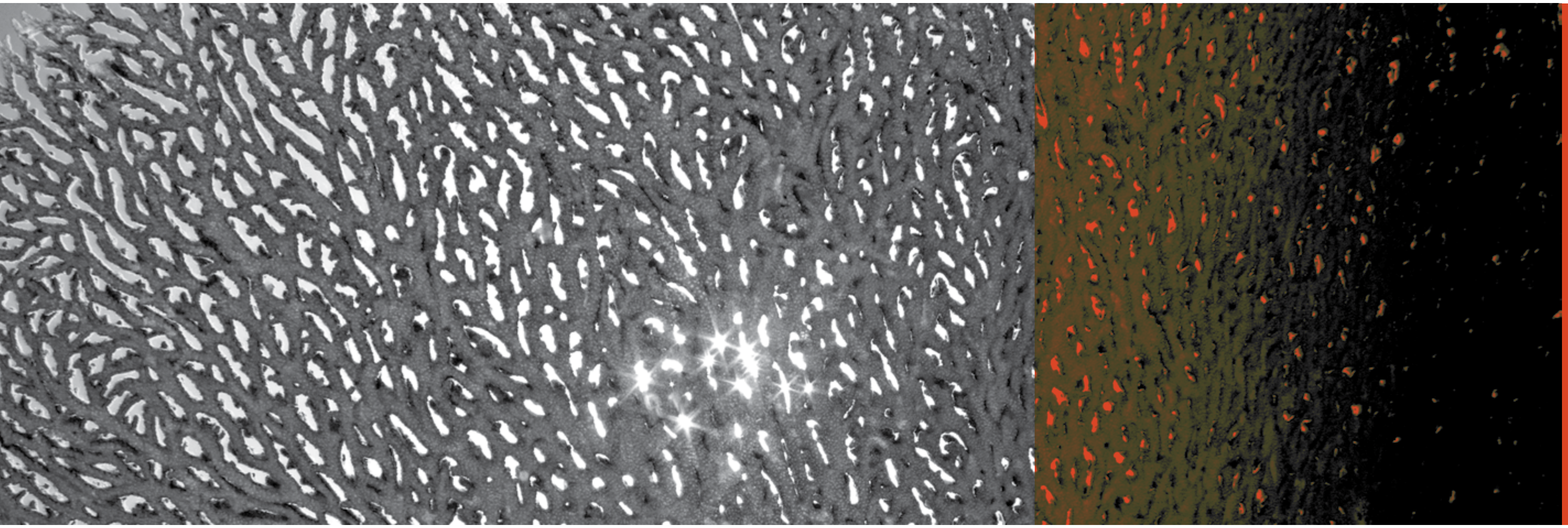


In addition to the abundance of adult corals at different locations, the rates of recruitment at Scott Reef are influenced by the direction of currents. Some locations, such as Inner East Hook, have consistently high rates of recruitment because eddying currents trap larvae; these locations are recruitment 'sinks'. Just a few kilometres away at Outer East Hook, consistently low recruitment is caused by currents carrying larvae away; these locations are 'sources' of recruitment.



At Scott Reef, there was a strong correlation between the rates of recruitment of spawning and brooding corals and the changes in coral cover before and after the mass coral bleaching. This finding has important implications for the reef, providing clear evidence that its recovery from disturbances primarily relies on the survivors, rather than being aided by the supply of larvae from other reefs in the region.

Researchers discovered a close relationship between the number of adult corals at Scott Reef and the number of new recruits and juvenile corals.



Coral Growth and Survival

After following colonies over many years, researchers concluded that the growth and survival of corals in favourable habitat conditions underlies the resilience of Scott Reef's communities to severe disturbances.

The isolation of Scott Reef has offered a rare opportunity to study the different factors influencing the recovery of coral communities from catastrophic disturbances. Although the reef's recovery is not aided by many recruits from other distant reefs in the region, it does benefit from the absence of many chronic pressures that affect reefs closer to the mainland, such as poor water quality and declining numbers of herbivorous fishes. Research at Scott Reef has revealed some new insights regarding the crucial role of growth and survival of new recruits in maintaining coral communities on isolated reefs – information that will assist in developing management strategies to maximise the reef's resilience to emerging disturbances acting on a global scale.

Understanding growth and survival

The capacity of a coral reef to withstand disturbances depends on the rates of growth and survival of the different coral colonies that make up the communities. In many places around the world this capacity has been compromised by a combination of human and natural disturbances that have resulted in long-term degradation.

To prevent and remedy these problems, it is important to not only describe the degradation of coral communities, but to fully understand why they occur. This approach includes quantifying the effects of pressures on the growth and survival of different stages of the coral's life cycle, in order to make predictions about how communities will respond to these pressures.

Existing studies have gone some way to clarifying these issues. For example, researchers know that table corals have faster growth but lower survival than those with a massive growth form. Growth and survival also tend to vary among different colony sizes within a coral species, so that the smallest colonies typically have much lower rates of survival than larger colonies.

However, many studies to date have been conducted on nearshore reefs or those under chronic stress – very different habitat conditions to those at Scott Reef and similar offshore reef systems.

Almost 6000 colonies of massive and table corals, across a range of size classes, were tagged and resurveyed over several years to measure rates of growth and survival. Tagged colonies included the table *Acropora* and massive *Goniastrea* corals, which are among the most abundant corals at Scott Reef. Many colonies were less than one centimetre in diameter, and finding these tiny corals among all the other organisms on the reef presented scientists with a considerable challenge.

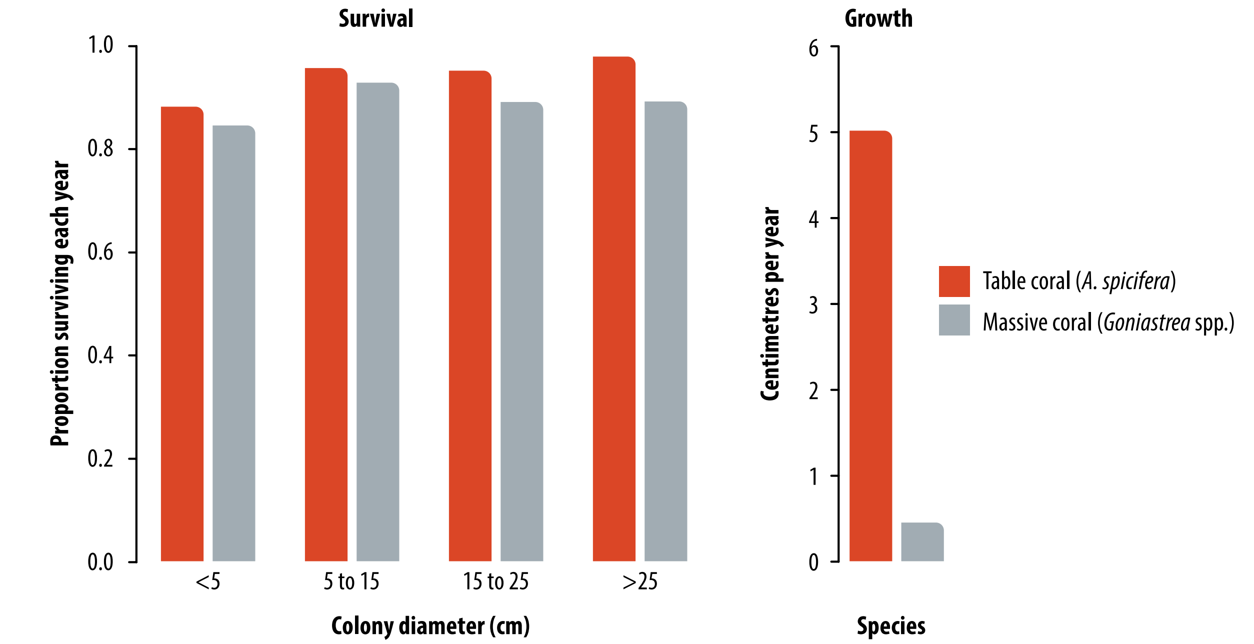
Interpreting changes

Between 2006 and 2010, researchers at Scott Reef measured annual rates of growth and survival for thousands of colonies of *Acropora spicifera* and *Goniastrea* spp. (*G. edwardsi* and *G. retiformis*) at several locations. These species were chosen because they are typical of the most common table and massive corals at the reef.

As expected, these studies revealed large variations in the rates of growth between the table and massive corals. Without major disturbances, the table coral *A. spicifera* increased in diameter by between two and nine centimetres each year, much faster than the massive *Goniastrea* corals, which generally grew less than one centimetre each year. Unexpectedly, however, there was little difference in survival, which averaged over 90 per cent per year for both groups of coral.

Table corals were, however, more susceptible than massive corals to the disturbances that affected the reef. After cyclone George struck in 2007, the growth and survival of table corals was reduced for several months at the most exposed locations. In those parts of the reef, survival rates were especially low among the largest colonies because they were most likely to be toppled over or fragmented by the powerful waves, which had comparatively little effect on the smallest colonies.

Some of the demographic research at Scott Reef produced more unexpected results. In both of the coral groups, there were only small differences in survival rates among the different colony size classes, which were consistently above 80 per cent per year from 2008 to 2010. Significantly, the smallest colonies had similar survival rates to the largest colonies, much higher than those often reported for other reefs.



In the absence of major disturbances, the corals at Scott Reef have high rates of survival, particularly the smaller colonies. From 2008 to 2010, the survival rates of all size classes of *Acropora spicifera* and *Goniastrea* spp. were consistently above 80 per cent per year. A disease outbreak and a moderate bleaching event in 2010 had little effect on their survival. However, growth rates varied considerably between the coral groups, with the table coral *A. spicifera* growing much faster than the massive *Goniastrea* spp.

Many of the *Acropora spicifera* colonies that were originally tagged in 2006 were still alive four years later, having grown from small juveniles into large adult colonies. For example, colony 'SL1-579' was only a few centimetres across when first tagged in 2006, but had grown to over 20 centimetres in diameter by 2010.

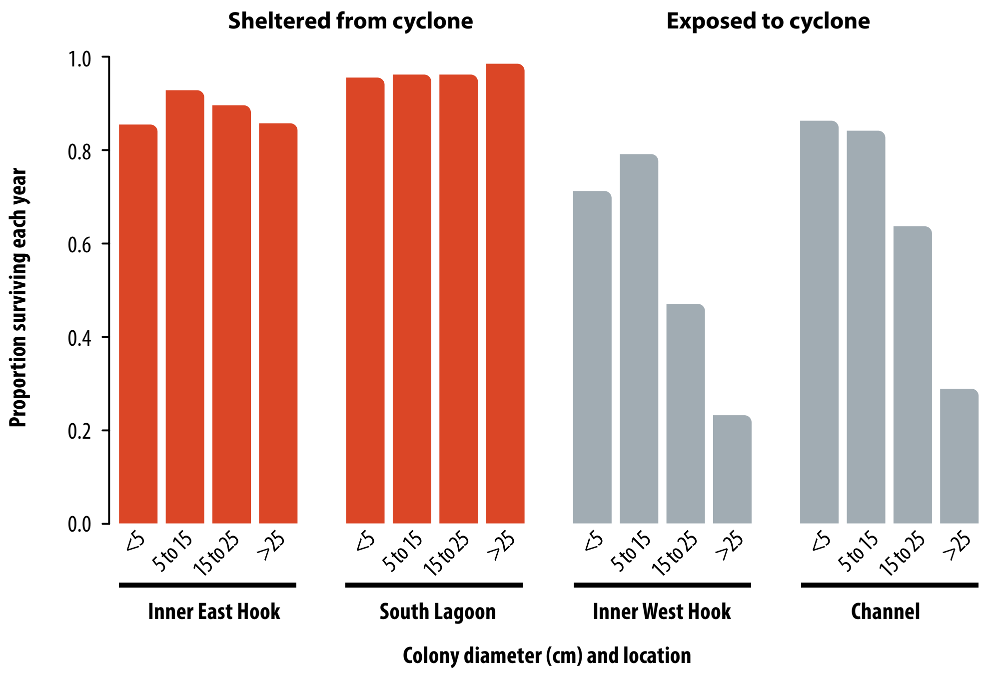
Favourable conditions at Scott Reef allowed coral communities to change from low cover and diversity following the mass bleaching in 1998, to high cover and diversity a decade later. A reef surface suitable for coral recruits, low algal cover and an abundance of herbivorous fishes, along with clear water, helped the corals to survive and grow.

Recovery from disturbances

The high growth and survival of corals at Scott Reef were particularly important to its recovery following the devastating mass bleaching in 1998. The destruction that occurred during this event was so severe that it affected all groups and sizes of coral colonies. The death of corals and the corresponding reductions in recruitment had long-lasting implications for the recovery of communities.

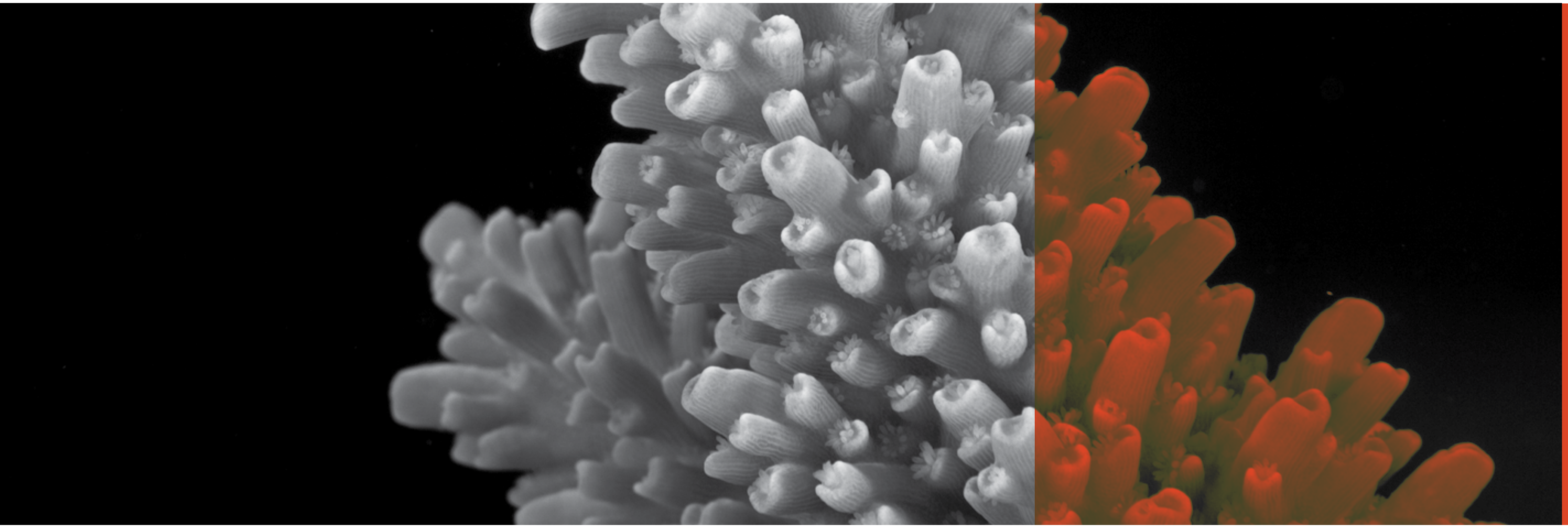
However, the high water temperatures that caused the mass bleaching persisted for only a few months, after which conditions returned to normal. The favourable conditions that were more typical at Scott Reef helped to ensure high rates of growth and survival during the recovery period. Those conditions included suitable space for recruitment, a low abundance of competing corals or macroalgae, a high abundance of herbivorous fishes and good water quality. Indeed, population models for the table corals from 2008 to 2010 indicated that the size of several populations increased by 20 per cent per year, suggesting they could double in size in less than five years. Consequently, the corals that survived the mass bleaching and the offspring they produced thrived in the favourable conditions, and communities had largely recovered from the coral bleaching within 12 years, much faster than initially predicted.

This illustrates how resilient coral reefs can be to periodic disturbances – even isolated coral reefs, such as Scott Reef, that do not receive a large supply of recruits from outside – provided local conditions remain favourable.



In areas exposed to cyclone George in 2007, survival of *Acropora spicifera* was much lower. The largest colonies were the worst affected by the cyclonic waves, some being killed instantly, while others died from their injuries over the following year.

REEF MONITORING



Monitoring Corals

Permanent monitoring locations were established at Scott Reef in 1994 and have been revisited most years since then. At each location, researchers surveyed transect lines running through coral communities at multiple sites and depths. This massive scale of sampling in space and time enables accurate estimates of the condition of the reef.

Coral reefs are dynamic environments that regularly undergo cycles of disturbance and recovery. Depending on how frequent and severe those disturbances are, recovery can take just a few years, or more than a decade. Because these cycles of disturbance span years, long-term monitoring is needed to reveal whether reefs are on a path to recovery, or degradation. However, few studies have gathered the kind of long-term data that allows inferences to be made about the condition of coral communities. The monitoring program at Scott Reef has been one of the longest of its kind, and the invaluable information it has gathered helps clarify what effect our changing climate is having on coral reefs, particularly rising water temperatures and the accompanying mass coral bleaching events.

Monitoring in space and time

Monitoring programs on coral reefs are primarily designed to track their condition – determining whether communities of corals and other organisms are within a natural cycle of disturbance and recovery, or if disturbances have become so severe that they are causing actual reef declines.

Coral reefs can recover relatively quickly from natural regimes of disturbance, which may even increase the diversity of organisms living on the reef by reducing the abundance of coral species that would otherwise outcompete others. However, a consensus is emerging among scientists that human activities are dramatically increasing disturbances to coral reefs. This raises serious concerns as to whether these human impacts are compromising the resilience of reefs to natural disturbances. Will one of these compounded effects become 'the straw that breaks the camel's back' for reefs? The complexity of coral reef ecosystems means this is a difficult question to answer.

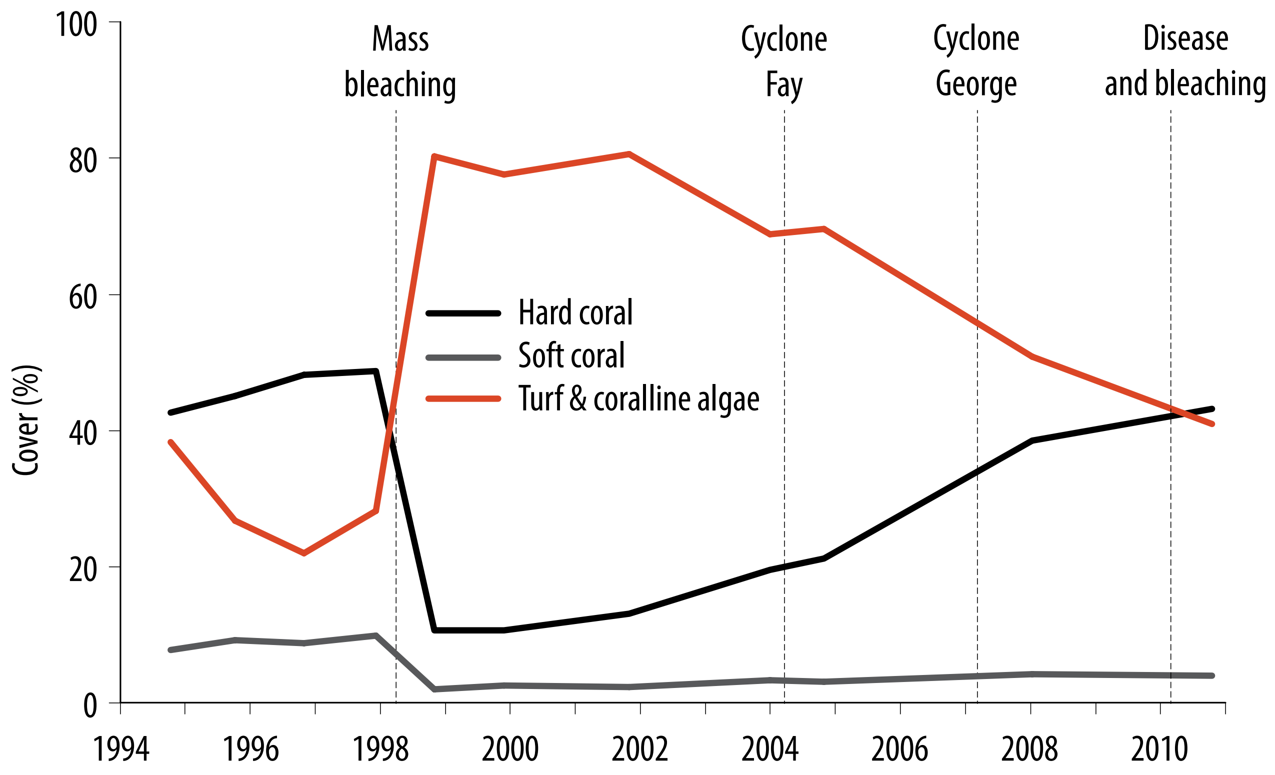
Cycles of disturbance and recovery vary from one coral reef to another, and even between different locations on the same reef. For this reason, a true understanding of the condition of a particular reef requires monitoring over many years at many locations.

Over almost 20 years, researchers at Scott Reef have resurveyed sections of the reef at varying depths and locations, along more than 10 kilometres of defined paths known as transect lines. During each survey, photographic records are taken along each transect and the organisms within each photograph identified. Over the course of the monitoring program this has amounted to around half a million records, providing a detailed description of the organisms present and how they vary through time, particularly in response to different disturbances.

Good times and bad

The most striking changes recorded during the long history of monitoring at Scott Reef followed the destruction caused by large disturbance events. Of even greater interest is how the reef has gradually recovered from these disturbances. Between 1994 and 2010, two events had particularly severe effects: a mass bleaching in 1998, and category 5 cyclone Fay in 2004. Others had moderate impacts: cyclone George in 2007, and the combination of a disease outbreak and bleaching event in 2010.

By far the worst of all these disturbances was the mass bleaching in 1998, which impacted all shallow water corals across the entire reef system. The subsequent disturbances were far less severe and more localised, usually having the effect of slowing the recovery from the 1998 event. The lingering effects of the mass bleaching are still evident today, and scientists have interpreted subsequent changes relative to that disturbance.



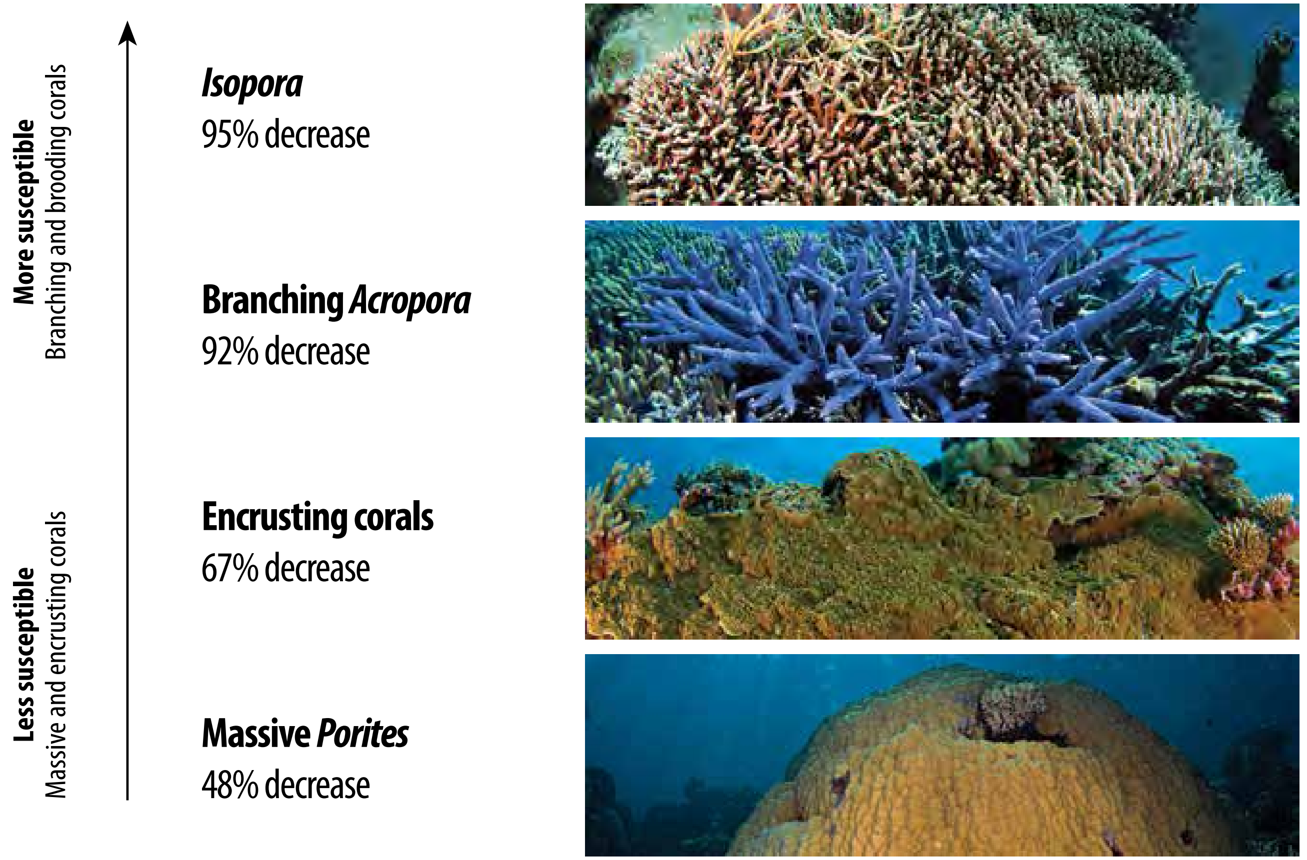
Communities of hard and soft corals at Scott Reef have been impacted by four major disturbances, of which the mass bleaching in 1998 was by far the worst. The high cover, particularly of branching corals, was dramatically reduced by this event and replaced by turf and coralline algae. A decade later, despite additional disturbances, the hard corals had largely recovered from the bleaching but the soft corals had returned to only half their previous cover.

In hot water

Before the 1998 bleaching there had not been a major disturbance at Scott Reef for more than a decade – the reef was densely covered in a highly diverse array of corals, including many large, old colonies.

However, in 1998 water temperatures became so extreme that most hard and soft corals across Scott Reef bleached and died, decreasing their cover by more than 80 per cent. The damage varied between locations on the reef, ranging from a 55 per cent to 95 per cent reduction in cover, depending on the maximum water temperatures and the number of susceptible corals. The cover of the most susceptible coral groups decreased by more than 90 per cent, these being corals with branching growth forms and those that reproduce by brooding larvae. In contrast, massive and encrusting corals were among those least affected by the bleaching, decreasing by around 50–75 per cent. The mortalities observed in all coral groups, even those best able to survive bleaching, gives an indication of just how severe this bleaching event was.

The reef surface that became available following the death of corals was quickly covered by coralline and turf algae. Importantly, however, it was not covered by macroalgae that can outcompete corals and also prevent them from recolonising.



Different groups of corals varied in their susceptibility to the mass bleaching at Scott Reef in 1998. Some groups decreased by more than 90 per cent, such as the brooding *Isopora* (top), while other groups decreased by less than 50 per cent, such as the massive *Porites* (bottom). Similar patterns of susceptibility to bleaching have been reported on other reefs around the world.

Recovery from bleaching

The mass bleaching in 1998 was so severe that scientists could see little evidence of recovery five years later. Some of the less susceptible corals had survived, albeit with injuries, and the regrowth of these corals contributed to small increases in coral cover. Recovery at some locations was also slowed by cyclone Fay in 2004. Despite its severity, cyclone Fay caused only small decreases in coral cover, because the most fragile corals were still rare. Nonetheless, many of the small recruits that had begun to recolonise the reef were killed, and some massive corals that had survived the 1998 bleaching event were damaged by the cyclone.

Ten years after the bleaching event increases in coral cover had accelerated, but at some locations this recovery had been slowed by yet another cyclone. Fortunately, the effects of cyclone George were far less severe than those of cyclone Fay three years earlier.

As the corals recolonised the reef, there were decreases in cover of coralline and turf algae, and a shift back to a pre-bleaching community was evident. Surveys conducted in 2010 showed that most communities had again become similar to their pre-bleaching state, although recovery at some locations was again slowed by further disturbances. An outbreak of disease and a moderate bleaching event in 2010 affected some corals and locations. The disease outbreak primarily affected table corals *(Acropora)* at two locations, whereas the bleaching mostly affected branching *Pocillopora* corals at a few locations.

Despite the additional disturbances, after 12 years the corals at Scott Reef had largely recovered from the mass bleaching. The diversity of coral genera and the average cover of hard corals had returned to their pre-bleaching level. The cover and types of corals at most locations were also similar to what had been observed before the disturbance, with some notable exceptions.

The puzzle of recovery

Determining whether coral communities at Scott Reef have fully recovered from the mass bleaching, or when they are likely to, is like solving a puzzle of many parts. The severity of the disturbance varied across the reef, depending on the water temperatures and the abundance of susceptible corals. Some locations were exposed to additional disturbances and their recovery was influenced by the rates of coral recruitment, growth and survival. All parts of this puzzle varied over space and time, and will continue to do so unpredictably into the future.

In this complex situation, researchers have contemplated what it means to say a reef has recovered from disturbance. Should coral cover at all locations on the reef be the same as before the disturbance? Should there be the same proportion of different types of corals at all locations? Although the coral cover and proportion of different corals at Scott Reef had mostly recovered by 2012, some variation existed between locations. Some coral communities recovered more fully than others, and these differences can be partly explained by both the life histories of the corals and their location on the reef.

Opposite page: In 1998, Scott Reef experienced high water temperatures that led to a widespread bleaching event. As the corals became stressed, they expelled the symbiotic algae from their tissue. With the loss of the algae that provide its colour, the coral appears white and 'bleached'. The mass bleaching in 1998 was catastrophic for Scott Reef, but a second bleaching in 2010 affected fewer corals.

Recovery and coral life histories

Corals have a range of different survival strategies and some are better equipped to deal with disturbances than others. Ten years after the mass bleaching, some corals may be considered winners, and others, losers.

Taking advantage of space made by the damage to other corals, table corals *(Acropora)* were the winners. These corals were only moderately affected by the bleaching and the larvae produced by the survivors dispersed across the reef and were able to colonise newly available space. In this instance, communities that were least affected by the mass bleaching produced new recruits that aided the recovery of those worst affected. The table corals grew and matured rapidly, and were among the dominant corals a decade later.

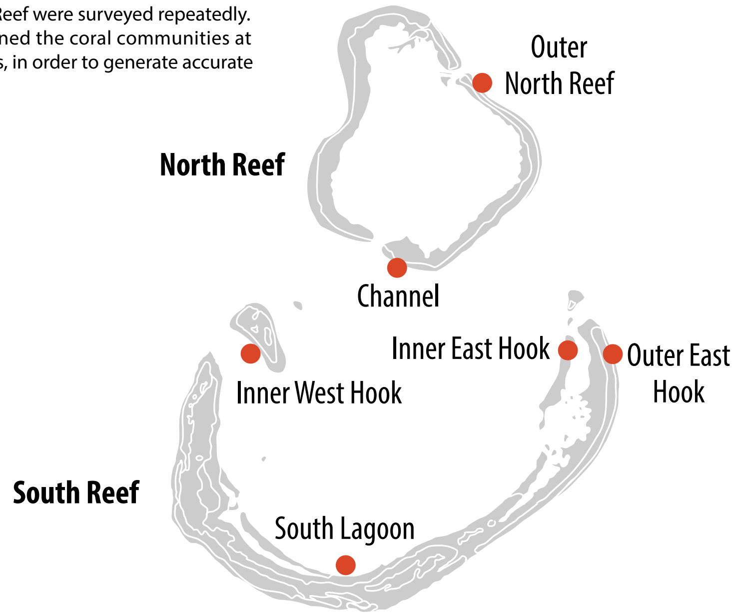
Other groups of corals may be considered the losers – at some sites, soft corals and branching *Isopora* were less abundant than before the bleaching. This is partly due to the way these corals reproduce and recolonise the reef. The recovery of soft corals depended on the growth of local survivors and their colonisation of adjacent areas by colony growth and division. The recovery of branching *Isopora* at each location also depended on the local survivors, as the brooded larvae they produce disperse over short distances and colonise nearby areas. Consequently, the recovery of these corals was much slower at the locations worst affected by the mass bleaching, because it was not aided by the supply of larvae from the less-affected areas.

It is important to note that while some corals can be considered winners and others losers at a particular point in space and time after the mass bleaching, other patterns will continue to emerge. For example, the table corals that were so abundant at Scott Reef in 2008 were most severely affected by the outbreak of disease in 2010, and are among the most susceptible to future cyclone damage. It is exactly because coral communities are so dynamic that long-term data are needed to assess the ongoing changes in their condition.

Monitoring Corals

The susceptibility of different groups of corals, and their modes of growth and reproduction, influenced the recovery of the reefs from the bleaching. Ten years later, table corals (opposite page) were the winners, having a much higher cover than before the bleaching – soft corals (below) were the losers, having around half the cover.

Monitoring locations across Scott Reef were surveyed repeatedly. At each location, scientists examined the coral communities at multiple sites, transects and depths, in order to generate accurate estimates of the reef's condition.



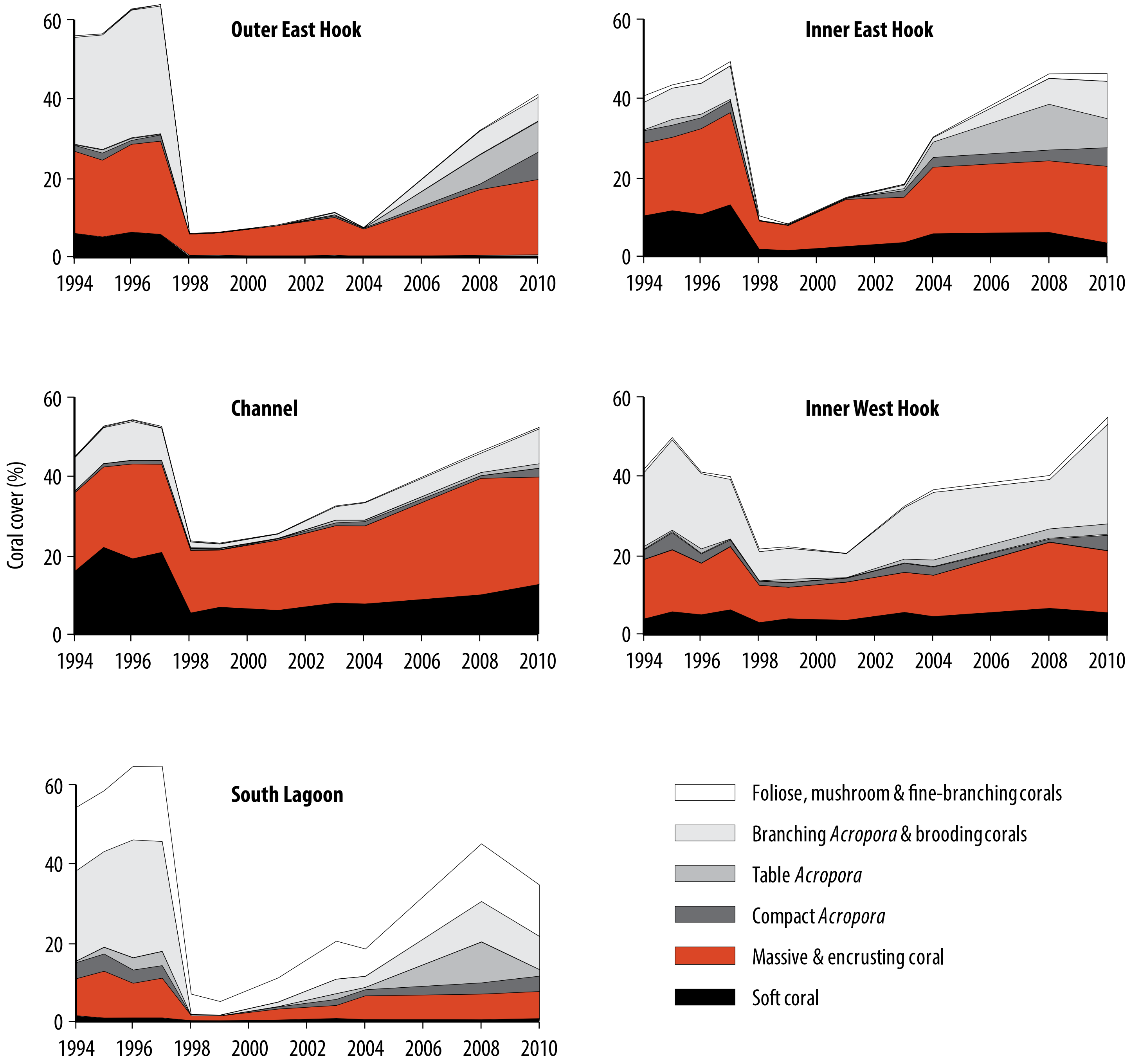
Recovery and coral locations

Each location around Scott Reef has distinct characteristics that have also influenced the recovery of coral communities from the mass bleaching. However, the conditions that favour one location in some situations can also leave its corals more vulnerable to other disturbances.

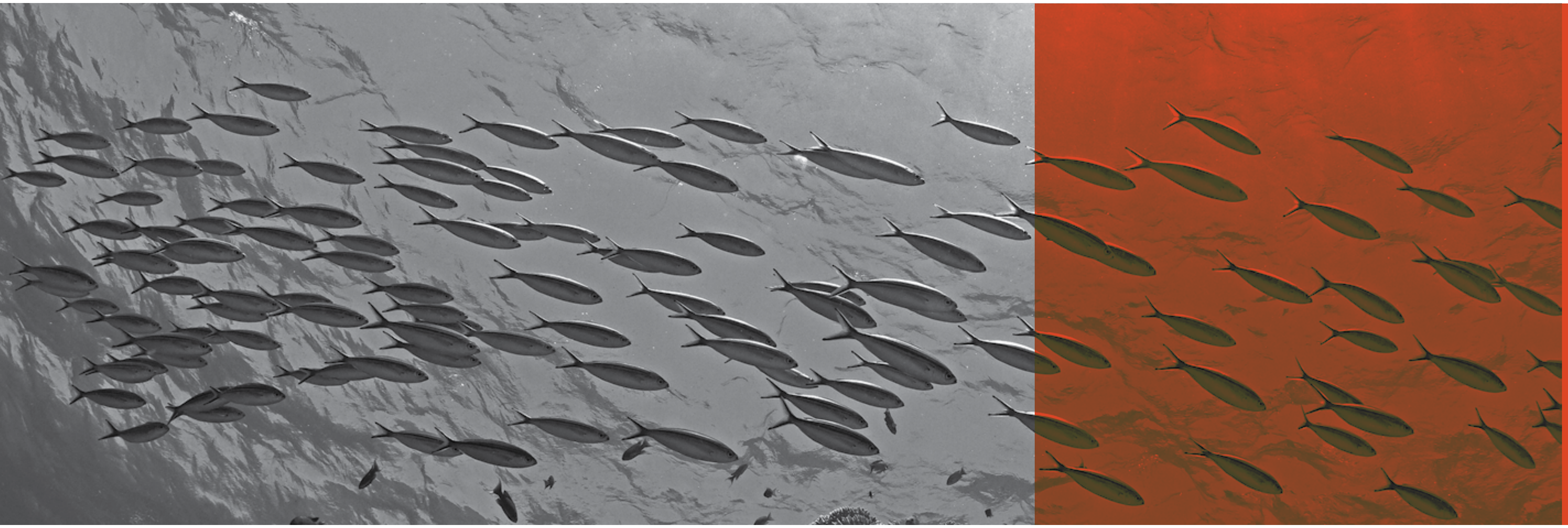
For example, the coral community at Inner West Hook was protected from the 1998 mass bleaching by the flow of cool water through the deep channel, but the location was also more exposed to large swells from passing cyclones. The opposite is true for corals in the southernmost part of the South Lagoon, which were sheltered from cyclone swells, but more susceptible to bleaching events and outbreaks of coral disease due to low water flow and higher turbidity.

The location of communities also influences the number of new coral recruits they receive and, therefore, their rates of recovery. Coral larvae are carried on currents before they settle onto the reef and grow into adults, so areas located in eddy systems can receive many new corals from upstream and recover faster. Researchers working at the reef found that the community at Inner East Hook received many coral recruits and recovered relatively quickly from the mass bleaching, whereas just a few kilometres away at Outer East Hook, coral larvae were carried away by the currents and this community was the slowest to recover.

The Scott Reef story is unique, and the long-term monitoring program documenting it is one of the few examining the recovery of an entire coral reef system from a catastrophic mass bleaching event. A shorter, less detailed study would not have captured the full cycle of impact and recovery, and would have been clouded by the variable recovery that occurs among locations. This research helps us to better understand the resilience of coral reefs to climate change, which is emerging as one of their biggest threats.



The coral communities at Scott Reef vary considerably among locations – some were hit badly by bleaching and cyclones, while others escaped more lightly. Some locations also recovered more rapidly than others, depending on the number of new corals arriving in that area in the years after the disturbance.



Monitoring Fishes

Slipping into the waters of Scott Reef, divers may find themselves surrounded by a flurry of activity. Larger fishes swim away quickly while dozens of smaller fishes shelter among the coral below. Descending deeper, divers observe brightly coloured butterflyfish and wrasse moving constantly across the reef. Massive parrotfish make scraping sounds as they bite off pieces of coral, while surgeonfish pick and scrape across algal mats. Predatory carnivores patrol in the distance as hundreds of small damselfish emerge and dart around before again sheltering among the corals.

The complex world of these reef fishes has been the subject of almost two decades of research. Scientists are now beginning to understand the changes within Scott Reef's fish communities, and how they are intrinsically linked to the corals that provide the fishes with food and shelter.

Discovering dependencies

Studying the many thousands of fishes that make their home among the corals and algae is an endeavour that requires great care and effort.

All researchers must first undergo dedicated training to standardise their identification of fish species and estimates of size and abundance, to minimise any biases among observers. At the reef, study sites must be approached carefully, so as not to disturb the fishes as they go about their daily activities.

The scientists swim through permanent sites replicated across Scott Reef. The large and mobile fish species are counted first before they swim away, and then the small, numerous species that shelter among the corals. These surveys have been repeated over many years, with hundreds of thousands of fishes counted and identified. When combined with the coral surveys at the same sites, these data provide new insights into the relationship between the corals and fishes at Scott Reef. It has long been known that corals are critical to the existence of reef fishes, but the extent to which these two groups of organisms influence each other, and the importance of fishes for the persistence of corals, has only recently been recognised.

Coral reefs are home to approximately one-quarter of all known marine fish species. They range from tiny blennies less than a centimetre long, which live in the sediment, to giant wrasse that roam across the reef. This diversity of fish life has traditionally been classified into taxonomic groups according to their physical features, such as body shape. However, as knowledge of their role in coral reef ecosystems has emerged, species of fish are also commonly classified into functional groups, which primarily reflect their feeding preferences. The abundance of these groups has important implications for the processes that maintain coral reefs. Indeed, functional groups of fishes are being used increasingly as one proxy for assessing the condition of coral reefs.

Studying the fish assemblages at Scott Reef involves identifying and counting a huge number and diversity of fish, ranging from the large mobile species such as the humphead wrasse (*Cheilinus undulatus*, pictured) to the smaller species that hide among the corals.

An incredible diversity of fish life exists on a coral reef. Fishes are traditionally classified into taxonomic groups according to evolutionary relationships and variations in body shape.

Functional fishes

Functional groups are used to classify fish species according to their role in the complex food web of the coral reef. Members of each functional group are specially adapted to feed in a certain way.

Carnivores feed mainly on fishes, crustaceans, molluscs and worms. Their different mouth types depend on their primary food source, ranging from the tiny razor sharp teeth of the lie-in-wait predators to the strong grinding plates of fish that consume hard-shelled molluscs. Carnivores occupy an influential place within the fish community – their removal allows prey to proliferate and can have flow-on effects to many other groups within the food chain.

Corallivores eat the tissue of hard and soft corals, and many have small mouths well suited to picking tiny coral polyps out of their skeletons. Their survival is directly linked to the abundance of corals, so they are a visible component of healthy reefs.

Herbivores bite off pieces of macroalgae or scrape away fine filaments of algae. They may have strong beak-like teeth adapted for scraping at hard surfaces. Herbivores play a critical role on coral reefs by controlling the amount of algae. When over-fishing reduces the numbers of herbivores, then algae can exclude and outcompete young corals – a situation that is difficult to reverse.

Detritivores feed on plant and animal material within the sediments and algal turfs common on coral reefs. Some have flexible teeth that comb through these algal turfs to sift out their food. By consuming detritus they recycle organic material on the reef and clear sediments from algal turfs for consumption by some herbivores.

Planktivores feed on tiny plankton in the water column, particularly small crustaceans. Planktivorous fishes are often brightly coloured and extremely abundant on the reefs, being an important food source for carnivorous fishes. Many coral reef fishes are planktivores during their larval stages, switching later to a different feeding mode.


Carnivores


Corallivores


Herbivores


Detritivores

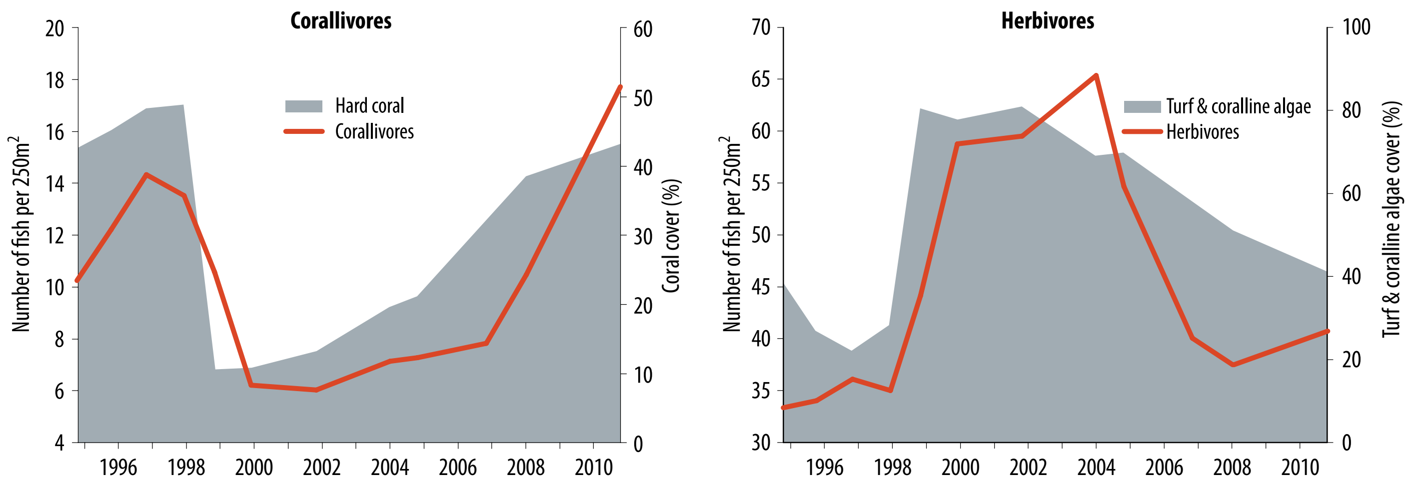

Planktivores

The effects of disturbance

The changes in community composition at Scott Reef, through a cycle of impact and recovery from mass bleaching, exemplify the close relationships that exist between corals and functional groups of fishes on the reef.

The effect of the mass bleaching event in 1998 was most striking on species that eat coral, such as butterflyfish. To a lesser extent, fishes that use coral for shelter, such as many damselfish, were also affected. In some instances, the relationships between the corals and fishes are quite specific. For example, decreases in the number of soft corals following the bleaching caused corresponding reductions in one species of butterflyfish *(Chaetodon melannotus)* – there were also comparable changes in a species of damselfish *(Chromis ternatensis)* and the branching *Isopora* coral within which it shelters. However, as the coral cover increased over the following decade so did the numbers of these species, along with other coral-dependent fishes.

For some fishes, the bleaching was a chance to prosper. The numbers of herbivores increased because dead coral skeletons were overgrown by algae – the abundance of detritivores also increased because they feed on the organisms within algal turfs and the sediment they trap. However, as the corals eventually recovered the cover of algae decreased, and there were corresponding reductions in the numbers of herbivores and detritivores.



Changes in the fish communities after the 1998 bleaching were closely linked to the fishes' food source. The number of corallivores (fish that eat coral) responded closely to changes in coral cover (left). For herbivores, changes in their algal food source corresponded to similar changes in numbers (right).

Vital herbivores

Another major theme in the study of fish communities at Scott Reef is the important role herbivorous fishes have played in aiding the recovery of corals following the 1998 bleaching event.

Numbers of herbivorous fishes increased sharply up to five years after the bleaching, controlling the cover of algae on the reef and maintaining space for coral larvae to recruit and grow to adulthood. In the absence of herbivores, this space may have otherwise been overgrown by algae, preventing corals from recolonising. The findings at Scott Reef support evidence gathered from many other studies around the world which shows that herbivores are vitally important to coral reefs.

The recovery of coral communities is thus tightly linked to the fish community. For Scott Reef to remain resilient to damaging events, it is important that all fishes, particularly herbivores, remain abundant within the ecosystem. In addition to protecting the reef from other pressures, ensuring that herbivores are not targeted by fishing is a vital step in safeguarding the future of the coral reef as a whole.

MEGAFAUNA

Turtles

Turtles may swim over 1000 kilometres to reach tiny Sandy Islet at Scott Reef, where they will lay several clutches of eggs before again returning to their foraging grounds.

Sandy Islet is a tiny spit of white sand in the vast blue expanse of the Indian Ocean. Aside from a few rocky outcrops, this unvegetated island is the only part of Scott Reef that is consistently above the high water mark. It is so small that a person can walk around it in less than half an hour, yet its existence is vital to the turtles that visit its shores to nest. Each summer, dozens of turtles make their way to the islet where they excavate shallow sandy nests to deposit large numbers of eggs. Several weeks later, hatchlings emerge and the young turtles make their way into the ocean. They may eventually return to the Sandy Islet as adults, to lay their own eggs.

Nesting season arrives

Each summer, many green turtles make the long swim to Sandy Islet to lay their eggs. The islet is unusual in that it lacks the rocks, vegetation or other obstacles that usually limit turtles nesting on a beach. As a result, they are able to move freely across the entire sand cay. In fact, turtles can be fussy about where they place their nests, and have been observed roaming across the sand but then returning to the water without nesting.

The turtles clearly show preferences for certain nesting areas on Sandy Islet – but these choices sometimes lead to disaster. During peak season, turtles will often excavate an existing nest while digging, killing the now-exposed eggs. In crowded conditions, some turtles may also dig below the tide line, where the nest becomes flooded by seawater and the eggs do not survive.

Since early 2006, when turtle monitoring began at Scott Reef, hundreds of green turtles *(Chelonia mydas)*, and a single hawksbill turtle *(Eretmochelys imbricata)*, have been observed nesting at Sandy Islet. During eight surveys, researchers have tagged more than 490 female green turtles, mostly during summer nesting seasons from late November to February.

The surveys revealed that the number of nesting green turtles at Sandy Islet varies markedly from one year to the next. During the summer of 2005–2006, for example, the average number of turtle tracks counted per night was 16 during peak nesting periods. In contrast, during the peak nesting period in 2008–2009 there were substantially more tracks – 53 per night in December 2008 and 72 per night in January 2009. The total nesting population of green turtles at Scott Reef was estimated at between 389 and 1476, but further studies are required to produce a more accurate estimate. The green turtles that nest at Scott Reef, and at Browse Island almost 200 kilometres to the east, form a separate group within the world's populations.

Scientists believe the number of turtles nesting at Scott Reef each year is influenced by a range of factors, including sea surface temperatures, fluctuating oceanographic and climatic conditions, and even the condition of feeding grounds hundreds of kilometres away.

Turtles

Turtle nesting at Sandy Islet

Mature green turtles (*Chelonia mydas*) leave their feeding grounds and swim hundreds of kilometres to lay eggs on Sandy Islet at Scott Reef. By the time the eggs hatch, the adults have already started the long journey back to their nearshore foraging areas. The emerging hatchlings swim into the open ocean, where they remain for several years before eventually travelling to the feeding grounds as sub-adults. When they are 20–50 years old, some will return to Sandy Islet as mature adults to continue the cycle of life.

Green turtles (*Chelonia mydas*) are widely distributed throughout the tropical and sub-tropical regions of the world's oceans. They are by far the most common species of turtle at Scott Reef and, since 2006, researchers have recorded hundreds of nesting females on Sandy Islet.

Each night during summer, many turtles dig carefully-positioned nests across Sandy Islet. Two to three months later, the hatchlings dig themselves free of the nest and instinctively head towards the waterline. The hatchlings begin their life alone, as their mothers have already left for feeding grounds hundreds of kilometres away.

New beginnings, old haunts

Turtles undertake a massive journey to reach Scott Reef and lay their eggs. The female green turtles that nest on Sandy Islet return, on average, every three to six years and lay up to five clutches of eggs in that season. Clutches can contain more than 100 eggs – a huge energy investment for the mother. Within the nests, about 75 per cent of hatchlings are incubated successfully and emerge from their eggs.

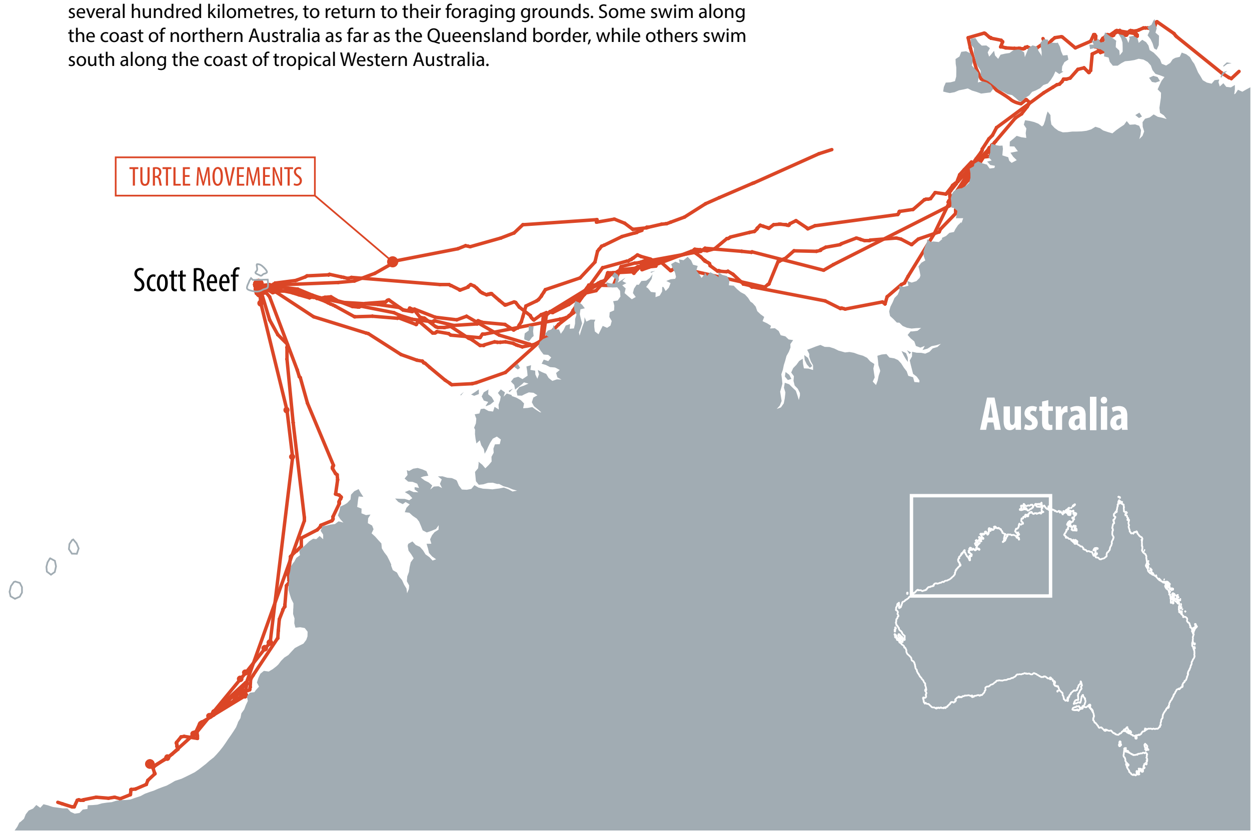
However, turtles cannot always rely on Sandy Islet as a safe repository for their eggs. Small and low-lying, the island is susceptible to the effects of tides, currents, waves and storms. In March 2004, cyclone Fay caused extreme waves and storm surges that eroded Sandy Islet, reducing its size by approximately one-third. Many eggs incubating on the island at this time may not have survived and, in the aftermath of the cyclone, nesting space was at a premium.

After laying a clutch of eggs, females return to the sea and spend around 10 days recuperating before returning to the beach to dig another nest and fill it with more eggs. Using direct observations and satellite tags to track the adult turtles' movements, researchers discovered that most females remained in shallow water less than three kilometres from Sandy Islet during the inter-nesting period.

Once the female turtles have finished depositing all their clutches of eggs into carefully constructed nests, they travel much further afield. Satellite tags attached to 12 female green turtles showed they were capable of moving quickly over large distances in search of foraging grounds. Some turtles headed north-east from Scott Reef to coastal waters in the Northern Territory, while others travelled south, reaching the Western Australian coast and continuing towards the Pilbara. While being tracked for an average period of 78 days, all female turtles travelled at least 490 kilometres, and some over 1000 kilometres, at an average speed of two kilometres per hour.

As their mothers reach the foraging grounds, newly hatched green turtles emerge from the nests on Sandy Islet and swim away from Scott Reef into the deeper waters of the open ocean. They will spend up to 20 years foraging at sea, eating pelagic species like jellyfish, before returning to reef habitats as sub-adults. Another decade is spent in shallow foraging grounds, which are generally reef areas with ample supplies of seagrass and algae. Compared with other reefs, including nearby Ashmore Reef, very few sub-adult turtles are seen at Scott Reef, probably because it lacks the extensive seagrass and algae beds that turtles feed in. At sexual maturity (20–50 years old), the turtles may make another long journey back to Scott Reef, where they mate and lay their eggs on Sandy Islet. The eggs hatch, hatchlings emerge, and the cycle continues.

After laying their eggs on Sandy Islet, the female turtles swim for months, covering several hundred kilometres, to return to their foraging grounds. Some swim along the coast of northern Australia as far as the Queensland border, while others swim south along the coast of tropical Western Australia.



Turtle hatchlings emerge from their sandy nests after incubating for 7–12 weeks. They make their way to the ocean and swim for deeper waters, completely independent and relying purely on their instincts for survival.

Whales and Dolphins

Every year, thousands of whales undertake migrations along the coast of Western Australia, from the food-rich Southern Ocean to their breeding grounds in the warmer waters of the Indian Ocean. Fishers and sailors have long known that during these epic voyages the enormous mammals track up the edge of the continental shelf, passing Scott Reef, where they occasionally stop to mingle with their dolphin relatives. Until recently, many important details about the whales' presence in the region were a mystery. Now, after years of careful work, including painstaking aerial surveys, satellite tagging, and the strategic deployment of noise loggers to record the animals' calls, scientists have a more complete understanding of whale movements in the region of Scott Reef.

Perseverance, ingenuity and technology

A major challenge for scientists studying Scott Reef is how best to describe the vast numbers of organisms that accumulate on and around the reef. But when it comes to whales, scientists confront a different obstacle. These giants are such infrequent visitors that monitoring must be carried out over large scales of space and time. Research teams working at Scott Reef have overcome this obstacle with a combination of perseverance, ingenuity and technology.

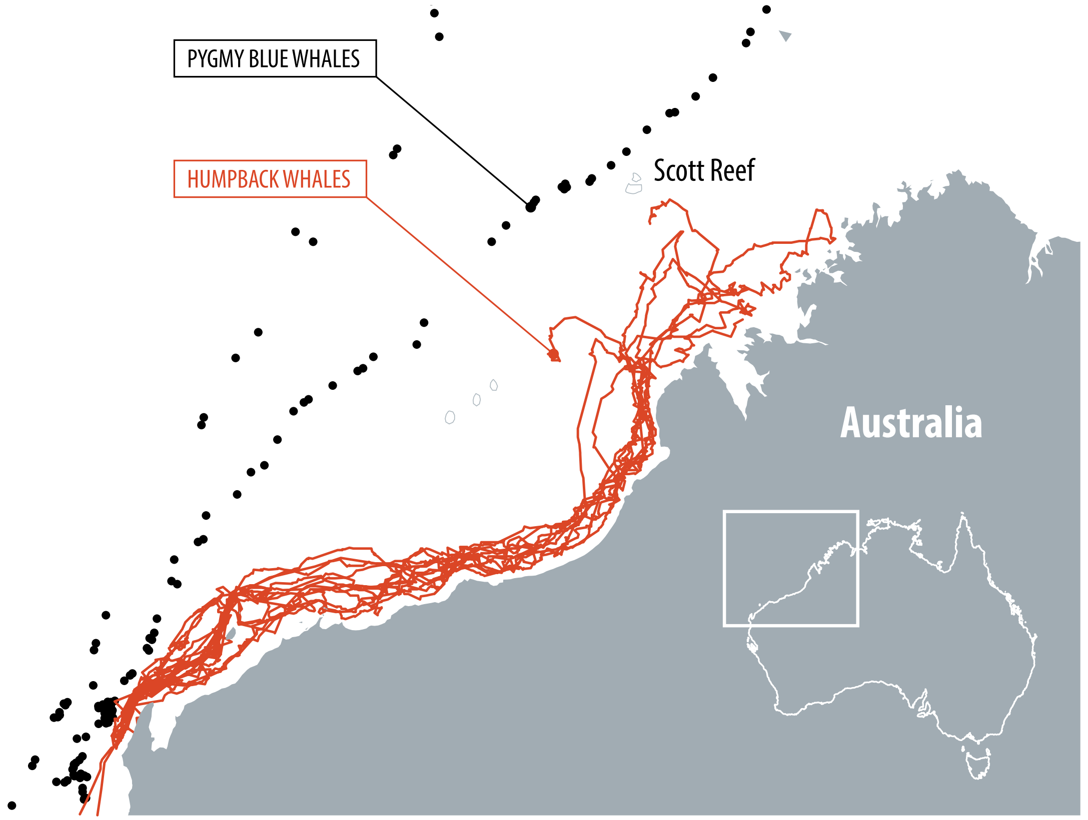
Long aerial surveys are used to record the location of whales on their annual migration. Trained spotters fly low over the ocean, searching for hours at a time to catch sight of a whale breaking the surface to breathe, slapping the water with its fins, or launching into the air. Spotters also search for 'whale footprints' – tell-tale disturbances on the sea surface that are evidence of a whale having recently passed by.

Accurately describing the migration path taken by whales over thousands of kilometres requires a different approach. Satellite tags are used to track the whales' long journey. Each time a tagged whale surfaces, its position is beamed to an orbiting satellite and back again, a process that is repeated over many months.

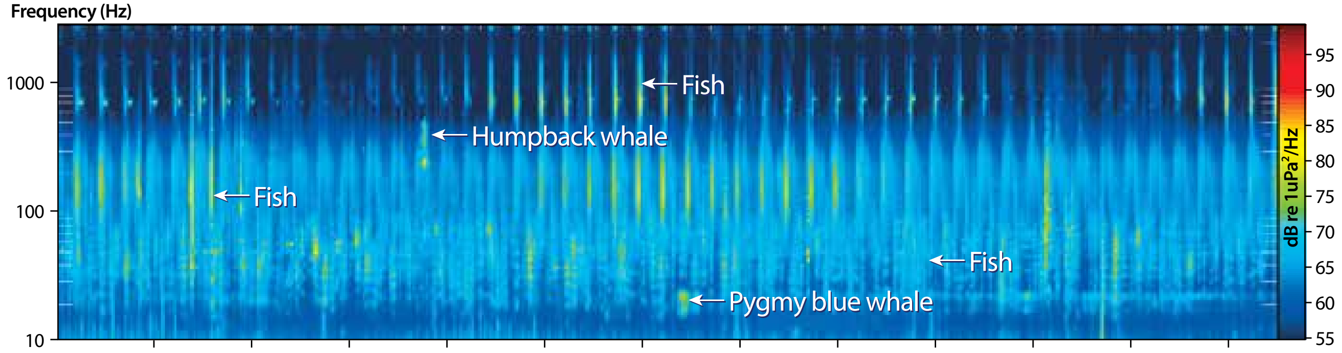
Perhaps the most innovative technique for whale monitoring at Scott Reef has been the use of underwater noise loggers – recorders specifically designed to capture the sound of whale songs. Analysing the particular frequencies of sound allows scientists to identify the species of whale from up to 50 kilometres away, and to distinguish their songs from the sounds of fish and other background noises. Those other background noises can include human activities, such as ships, seismic surveys and exploratory drilling, and even illegal dynamite fishing.

The combination of these techniques has revealed the presence of at least five species of whales in the Scott Reef region, including large whales on their annual migrations. Species of whales and dolphins recorded to date include humpback whales *(Megaptera novaeangliae)*, pygmy blue whales *(Balaenoptera musculus brevicauda)*, Bryde's whales *(Balaenoptera edeni)*, false killer whales *(Pseudorca crassidens)* and dwarf minke whales *(Balaenoptera acutorostrata)*.

Long flights that systematically cover vast distances are necessary to find evidence of whales on their annual migration. Observers may spot disturbances remaining on the ocean's surface or, more obviously, whales surfacing to breathe or breaching impressively.



Humpback whales *(Megaptera novaeangliae)* and pygmy blue whales *(Balaenoptera musculus brevicauda)* were tracked during their migration using satellite tags. Most humpback whales stay close to the Western Australian coast, but some visit Scott Reef in small groups. Pygmy blue whales, heading north past Scott Reef, mostly travelled alone or in pairs.



Underwater noise loggers recorded fish sounds, whale songs and other background noises. Loggers can capture the sounds of whales up to 50 kilometres away, and researchers are able to identify different whale species by the frequency of their calls.

Humpback whales

Humpback whales migrate annually, moving between summer feeding grounds in Antarctica and tropical breeding aggregations in winter. Past whaling activity nearly wiped out the Western Australian humpback population, but after reaching an estimated low of 1000 individuals the population had recovered to approximately 22,000 in 2008, with scientists projecting that numbers will continue to rise.

Noise loggers have been used to monitor the movement of male humpback whales at Scott Reef, as it is thought that the females do not sing. According to the loggers' recordings, males were present in low numbers both in South Reef 's lagoon and around the outside of Scott Reef from late June to early October each year. During this period, aerial surveys were also conducted to investigate their movement through the region.

Between July and October 2009, scientists conducted five aerial surveys between Scott Reef and the Dampier Peninsula, north of Broome, recording 90 adults and nine calves in 83 groups. Ten additional aerial surveys between June and October 2010 recorded 93 adults and five calves in 73 groups. Most of the humpbacks stayed close to the Kimberley coast, giving birth in the Camden Sound area, with total numbers estimated at 13,000 during the northern migration.

Around Scott Reef in 2009, researchers recorded 12 adults and two calves. Six of the sightings were 5–20 kilometres to the west of the South Reef, while eight of the sightings were within the South Reef lagoon or immediately to the east of the South Reef. In 2010 there were confirmed sightings of nine adults and two calves within the area.

Humpback whales grow to approximately 15 metres in length, and spend summers feeding in Antarctica before migrating north in winter to breed. Both adult and calf humpback whales have been observed visiting Scott Reef. Humpbacks are baleen whales and feed predominantly on small crustaceans called krill.

Pygmy blue whales

Blue whales, the largest living animals, are found in all the oceans of the world. In Australia, there are two recognised subspecies, the true blue whale *(Balaenoptera musculus intermedia)* and the pygmy blue whale *(Balaenoptera musculus brevicauda)*. Despite its name, the pygmy blue whale is only a few metres shorter than the true blue whale, growing up to 25 metres in length. Of the two southern subspecies, only the pygmy blue whale has been observed in the region around Scott Reef.

Noise loggers set along the coast of Western Australia have detected an annual migration of pygmy blue whales past Exmouth, the Montebello Islands and the Scott Reef region. These whales passed Scott Reef heading south between October and January, and again between April and August as they swam north.

Pygmy blue whales tend to pass to the west of Scott Reef, closer to the edge of the continental shelf, and prefer to travel alone or in small groups. For example, most (78 per cent) of the calls recorded around Scott Reef between 2006 and 2009 were from lone whales, with a much smaller number of calls from a pair of whales (18 per cent) or from a group of three or more whales (four per cent).

Scientists have not seen large groups of pygmy blue whales travelling through the Scott Reef area. During 40 days of intensive vessel surveys between Scott Reef and the mainland from June to November 2008, researchers saw just one pygmy blue whale heading north, and six moving south. Of the southbound whales, five were in the channel between North and South Reef, while one was about 50 kilometres to the west of Scott Reef. The northbound whale was observed approximately 200 kilometres to the east of Scott Reef.

Pygmy blue whales grow to approximately 25 metres in length and, like humpbacks, spend summers feeding on krill in temperate waters before migrating north to spend winter in the warmer waters of the Indian Ocean.

Dolphins

Dolphins at Scott Reef far outnumber their larger relatives, the great whales. In 2008, over 3000 dolphins were sighted from at least 10 species. Of these, the long-snouted spinner dolphins *(Stenella longirostris)* were by far the most common and conspicuous – over 1000 individuals were counted. Spinner dolphins are known for their spectacular acrobatics and their ability to rotate while leaping into the air.

Species of dolphin seen less often, but still numbering in their hundreds, were bottlenose dolphins (*Tursiops* spp.) and the short beaked common dolphin *(Delphinus delphis)*. Other members of the dolphin family observed at Scott Reef, which more closely resemble whales in many ways, were the pilot whales and false killer whales.

Most dolphins encountered were swimming in pods – social groups that can contain hundreds of individuals. The average size of the group varied considerably between seasons, with much smaller pods seen during June-July (an average of 13 dolphins per pod) than in October-November (an average of 37 dolphins per pod). Some species of dolphin are considered to be migratory, but patterns can vary even within a single species: some individuals stay within their home range year round while others move among wider areas. It remains to be discovered just how many of the dolphins at Scott Reef reside there permanently.

The most common species of dolphin at Scott Reef is the long-snouted spinner dolphin *(Stenella longirostris)*, which lives in pods of up to hundreds of individuals.

At least 10 species of dolphin inhabit Scott Reef. They are conspicuous both because of their abundance and their amazing capacity for acrobatics, in and out of the water.

Conclusions

Over millions of years, Scott Reef has demonstrated a remarkable ability to survive in a dynamic environment, including the capacity to withstand large changes in sea level over geological time. Like other coral reefs around the world, it has been affected by intense cyclones and severe coral bleaching in recent decades. But Scott Reef is distinguished by its recovery from these disturbances, and the reasons for its resilience are among the most important lessons learnt from the years spent studying the reef.

The recovery of Scott Reef illustrates that minimising local pressures can be vital to coral reefs, assisting their recovery from global threats that are so difficult to control. Favourable local conditions have enabled Scott Reef to recover from a mass bleaching in 1998 and other disturbances over the following decade, even with a limited supply of new organisms from other distant reefs.

Scientific research at Scott Reef has also produced many other important discoveries, leading to a better understanding of how different organisms are linked to each other and to their environment. Scientists have revealed ways in which corals and fishes depend on each other for survival; how corals and their symbiotic algae can adapt to extreme changes in depth; the effect of water movements on the flow of nutrients and larvae; and the importance of the reef to migratory turtles and whales. These and other discoveries have made important contributions to our understanding of Scott Reef, as well as other coral reefs around the world.

Despite the numerous discoveries made at Scott Reef over the past 20 years, many questions still remain. In particular, what does the future hold for the reef and the countless organisms that depend on it for their survival? Will the reef persist in its current state, or will more disturbances compromise its condition? Scientists continue to search for the knowledge to answer these questions, to monitor changes in ecosystem health, and to provide managers with the tools to better preserve the irreplaceable richness of Scott Reef.

As with all coral reef ecosystems, maintaining the health of Scott Reef into the future will depend on our ability to manage both the local and global pressures arising from human activities – an ever-increasing challenge for us all.

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