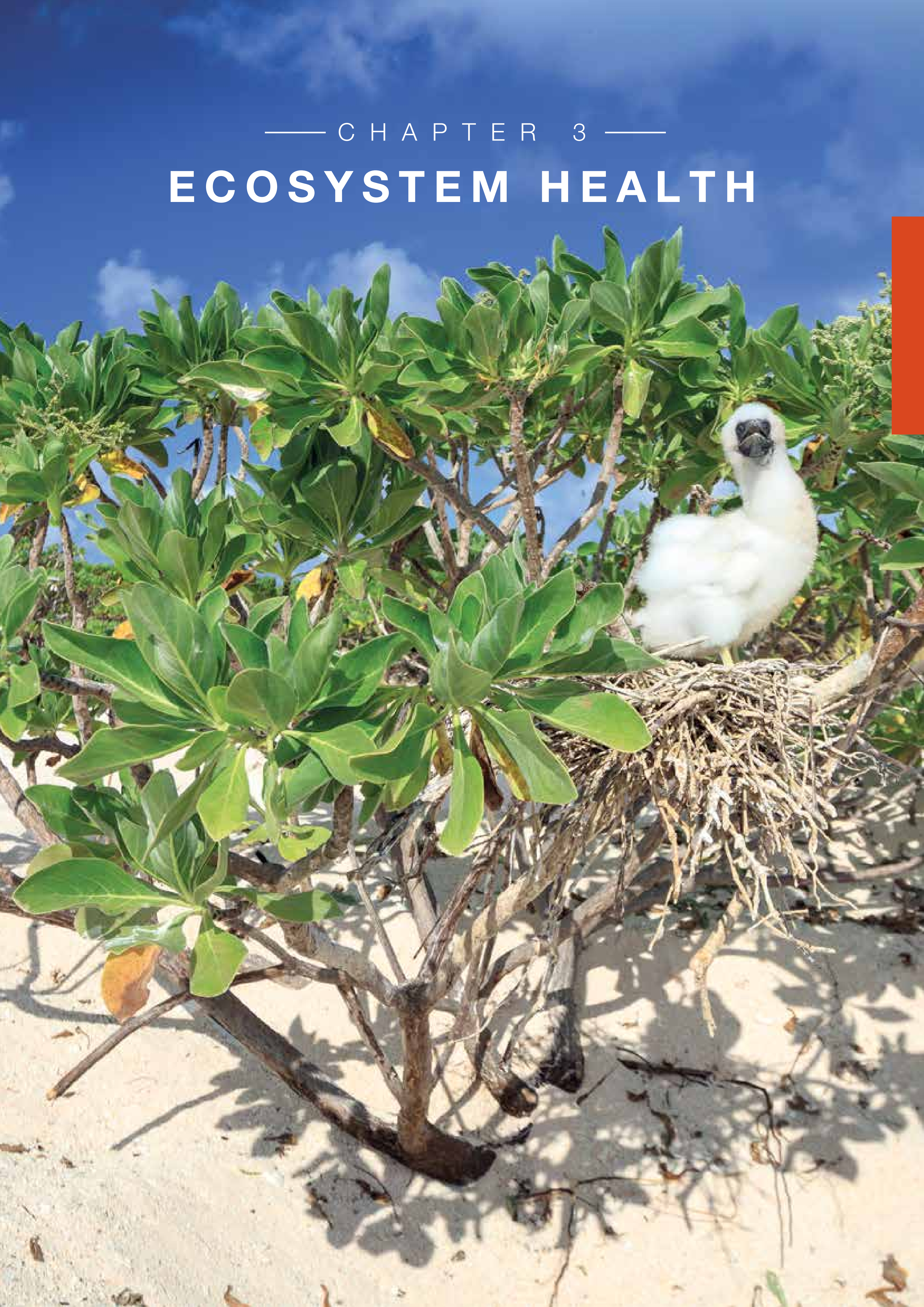
CHAPTER 3

ECOSYSTEM HEALTH



« *A seabird chick waits for a parent to return with food — recruitment of new individuals into populations is an important ecological process.* © Tane Sinclair-Taylor

ECOSYSTEM HEALTH

(an element of natural heritage)

'an assessment of the current health of the ecosystem within the Great Barrier Reef Region and of the ecosystem outside that region to the extent that it affects that region', s 54(3)(a) of the *Great Barrier Reef Marine Park Act 1975*

3.1 Background

The Region's ecosystem includes all of its species interacting together within the physical and chemical environment. Ecosystem health encompasses these key interactions and processes that operate to keep an ecosystem functioning. For example, without the process of larval dispersal by currents, species and habitats would not replenish after disturbances. Broadscale impacts have more potential than smaller localised impacts to disrupt ecosystem processes.

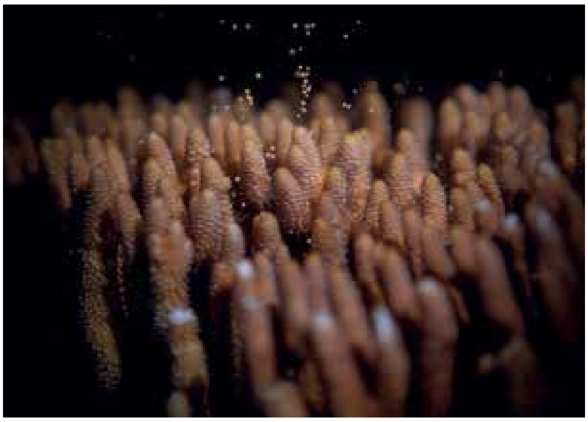
Change in biodiversity can only be used as an approximate indicator of ecosystem status.[418,419] An ecosystem is considered healthy if it is able to maintain its structure and function in the face of external pressures.[420] A functioning ecosystem provides a range of services and benefits to humans, including supporting, provisioning, regulating and cultural services.[421,422]

This systematic assessment of the health of the Reef ecosystem is based on five assessment criteria, which consider the Region's main processes (Figure 3.1):

- physical processes
- chemical processes
- ecological processes
- coastal ecosystems that support the Great Barrier Reef
- outbreaks of disease, introduced species and pest species.

The scope of the components assessed remain the same as the previous Outlook Report, with a few minor updates to titles (Appendix 2).

Predation is a key ecological process. © Tane Sinclair-Taylor



Coral spawning is a well known recruitment phenomenon. © Mikaela Nordborg

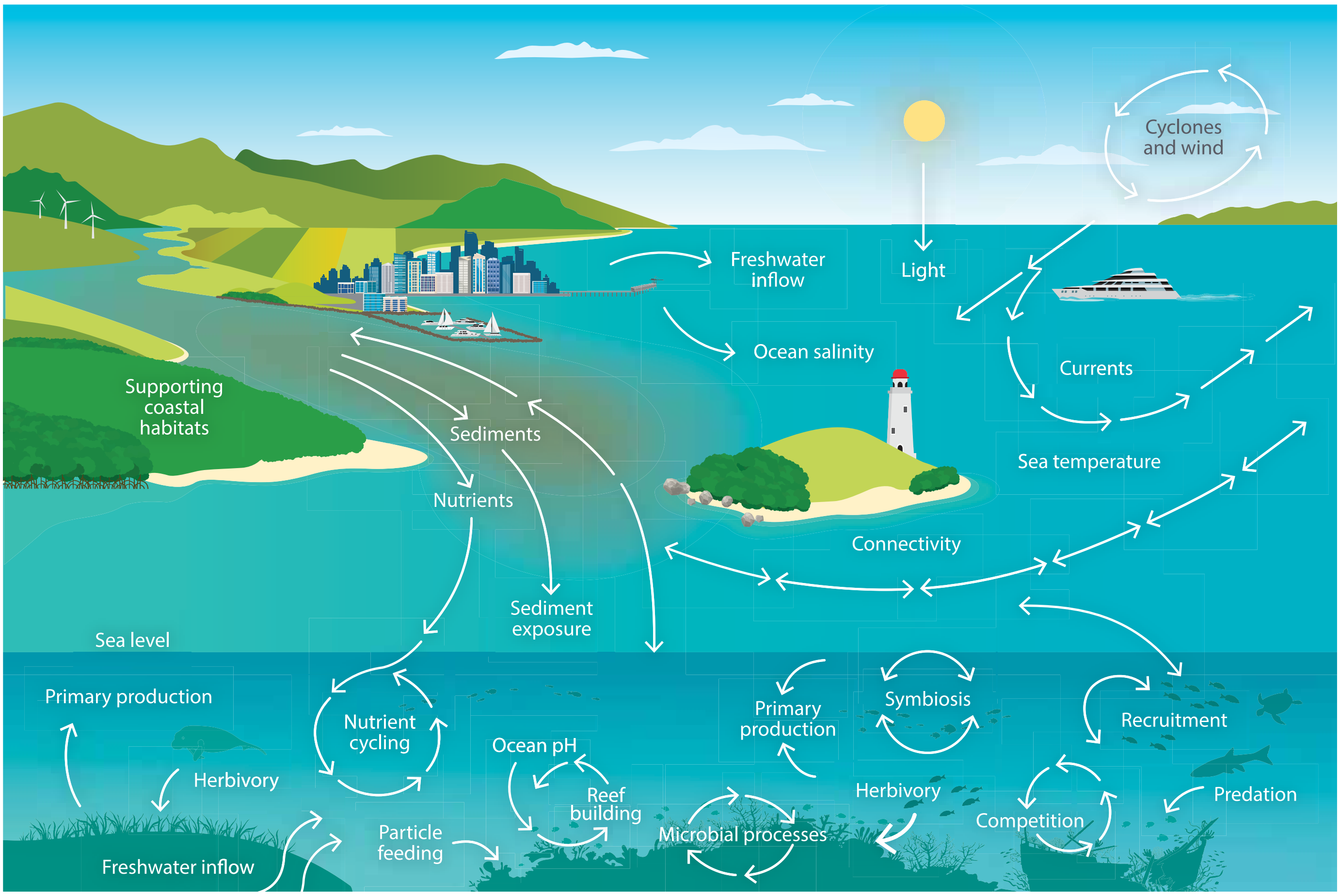


Figure 3.1 Major physical, chemical and ecological processes
The health of the Reef ecosystem is assessed by considering its physical, chemical and ecological processes as well as the condition of its supporting coastal ecosystems. Outbreaks of pests and diseases are also considered as a guide to overall health.

3.2 Current condition and trends of physical processes

Seven physical processes are graded. Currents remain in very good condition and four physical processes (cyclones and wind, freshwater inflow, sea level and light) remain in good condition. Sediment exposure remains poor and sea temperature has deteriorated to very poor.

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Full assessment summary: see Section 3.7.1

3.2.1 Currents

Types of currents that affect the Region include oceanic, wind-driven and tidal. Currents support biodiversity and ecosystem functions within the Region, via exchange of shelf and Coral Sea waters and upwelling, promoting larval dispersal and connectivity.[152,423,424,425,426] Currents also transport pollutants and contaminants, such as land-based run-off, dredge spoil and microplastics, from Australia and distant regions to the Reef.[161]

The East Australian Current has already warmed and extended south by approximately 350 kilometres

Two branches of the South Equatorial Current enter the Region and split into the North Queensland Current (Hiri Current) flowing north and the East Australian Current flowing south.[426] The South Equatorial Current influences the Region at multiple locations and controls the relative strength of the North Queensland Current and the East Australian Current.[426] The East Australian Current is the predominant current around reefs and island chains, and together with tidal currents create eddies, jets and other fine-scale circulation features that affect local reef-scale processes and connectivity.[152] Generally, the North Queensland Current and East Australian Current are of similar strength. However, this changes during extreme El Niño and La Niña events. The southerly flow is more dominant on mid-shelf reefs during El Niño and the northern flow is stronger during La Niña.[424]

While currents as a physical process in the Region have continued to connect and transport species and nutrients, changes are occurring. For example, the East Australian Current has already warmed and has extended south of the Region by approximately 350 kilometres.[427] This pattern is expected to increase under climate change projections (Section 6.3). Overall, there have been no significant changes to currents within the Region, and they continue to transport and connect species and habitats.

3.2.2 Cyclones and wind

Cyclones track through much of the world's tropical regions and are significant drivers of ecosystem change.[428] During El Niño events, there are typically fewer tropical cyclones than average, while more tend to occur during La Niña events. Destructive waves generated by cyclones can cause extensive damage; for example, they can kill coral and damage reef structure[429], destroy mangrove forests[54] and cause high levels of erosion on islands.[430]

Since 2014, over 50 per cent of the Reef area has been exposed to destructive waves from six tropical cyclones

Damage to ecosystems from cyclones is usually patchy and highly variable at local scales (less than 10 metres).[274,431,432] The likelihood of destructive waves in a particular location depends on the cyclone's intensity, size, speed of forward motion and fetch.[433,434] Weaker cyclones of sufficient fetch that move slowly over areas can generate waves that are just as destructive as those from the strongest cyclone.[434] The spatial[435] and temporal distributions[436] of cyclones are important attributes in assessing the vulnerability of habitats and species, as is the overall disturbance history.[437]

Long-term monitoring indicates that, before the 2016 mass bleaching, cyclones had caused the greatest overall coral loss in the Region.[438] Since 2014, six tropical cyclones have made landfall along the Region's coastline, with five of those being severe (Category 3 or above, Figure 3.2), affecting 68 per cent of reef area in the Region.[434] Past cyclones have caused extensive declines in hard coral cover[432] and coral trout abundance.[439] Surveys conducted following cyclone Ita in 2014 found a decline in biomass of several damselfish species and an increase in herbivores around Lizard Island.[274] The effects of cyclone Debbie on reefs in the Whitsundays are still being determined. However, six reefs surveyed in 2017 exhibited an average 70 per cent loss of coral cover at two metres depth and 64 per cent loss at five metres depth, but this ranged up to 98 per cent in some areas.[440] Because cyclone Debbie moved extremely slowly (average forward speed of just over seven kilometres per hour), gales near the reefs persisted for a maximum of 56 hours, making it the third most persistent cyclone since 1985.[441,442] Although the cumulative effect of cyclone impacts since 2014 has not been quantified, it is likely that many affected species are still recovering.

Wind influences the marine ecosystem, shaping islands and coastlines, and influencing waves and currents and the pathways of marine pollution.[443,444] Established wind patterns also influence reef animals, such as corals[445] and fish.[446] Any changes in wind patterns may also alter connectivity within the Region, via the distribution of wind-borne seeds and larvae from coral, fish and invertebrates.[447,448,449,450]

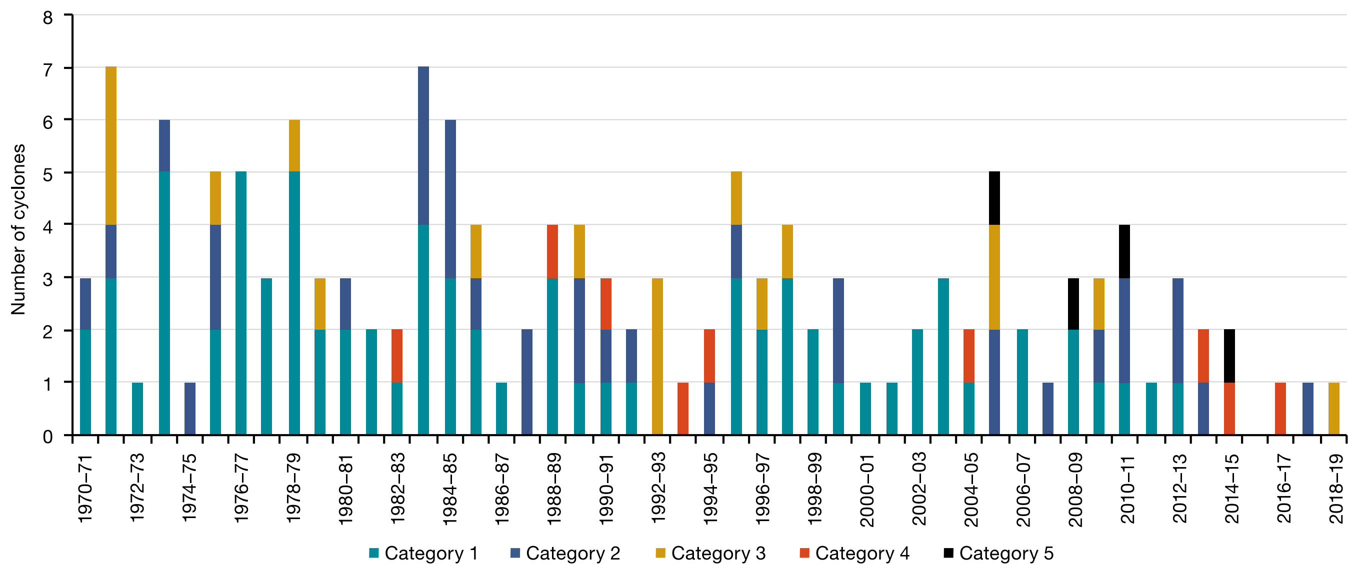

Figure 3.2 Number and severity of cyclones, 1970–71 to 2018–19
Five severe cyclones (Category 3, 4 or 5) have affected the Region since 2013–14. Source: Bureau of Meteorology 2019[451]

Wind patterns and the intensity of cyclones have not measurably changed since the 2014 Outlook Report assessment.[452] Forward speeds of tropical cyclones over Australia have slowed by an average of 22 per cent between 1946 and 2016; this slowdown has been linked to rising temperatures associated with human-induced climate change.[453] Nonetheless, these changes have not yet had a demonstrable effect on ecosystem function and no consistent trend was detected in the 2014–2018 assessment period.

3.2.3 Freshwater inflow

Rivers and streams from the Catchment drain an approximate area of 424,000 square kilometres. Rivers in the Cape York, Wet Tropics and Mackay–Whitsunday natural resource management (NRM) areas generally have groundwater flow all year round and high rainfall events every year. By comparison, the Burdekin, Fitzroy and Burnett–Mary areas have less frequent but higher discharge events.[454,455]

Between 2013 and 2018, freshwater flow was near or below the long-term average for the Catchment

Freshwater input lowers salinity and introduces sediment, nutrients, pesticides, herbicides and other pollutants into the marine environment, which can have significant effects on inshore and mid-shelf habitats and species.[43,456,457] Lower salinity and light can lead to localised coral and seagrass mortality. For example, a large-scale flood plume from the Fitzroy River in 2010 lowered seawater salinity and caused 40–100 per cent coral mortality at Keppel Bay.[458]

Freshwater flow has also become more variable since European settlement, with more extremes experienced during wet and dry seasons.[459] Substantial changes in freshwater flow into the marine environment appear to be associated with changes in the El Niño-Southern Oscillation.[457] Cores taken from long-lived corals indicate that the frequency of high freshwater flows into the Region has increased over the past two centuries, from every 20 years in 1748–1847 to every six years in 1948–2011.[457,460] Along with climate change, extensive land clearing and changes in land use (Section 6.4) have occurred over this time period, and are likely to have altered hydrology, contributing to higher freshwater discharges.[457]

The frequency of freshwater flows has increased cumulative pressures on the Region since European settlement. This has affected recovery of inshore coral and seagrass habitats, which are inhibited by the reduced time between high-flow periods.[59,457,461] Despite this longer-term change, freshwater flow was near or below the long-term average for the Catchment between 2013 and 2018, similar to the period 2004–2007 (Figure 3.3).[460] The correlation between low rainfall, low flows and coral recovery was observed in the Burdekin region from 2013 to 2018, where coral condition improved from poor to moderate.[440,462,463] As described above, human activities have caused significant changes in freshwater inflow, although over the past five years freshwater flow has been near or below the long-term average, resulting in a stable trend in condition since 2014.

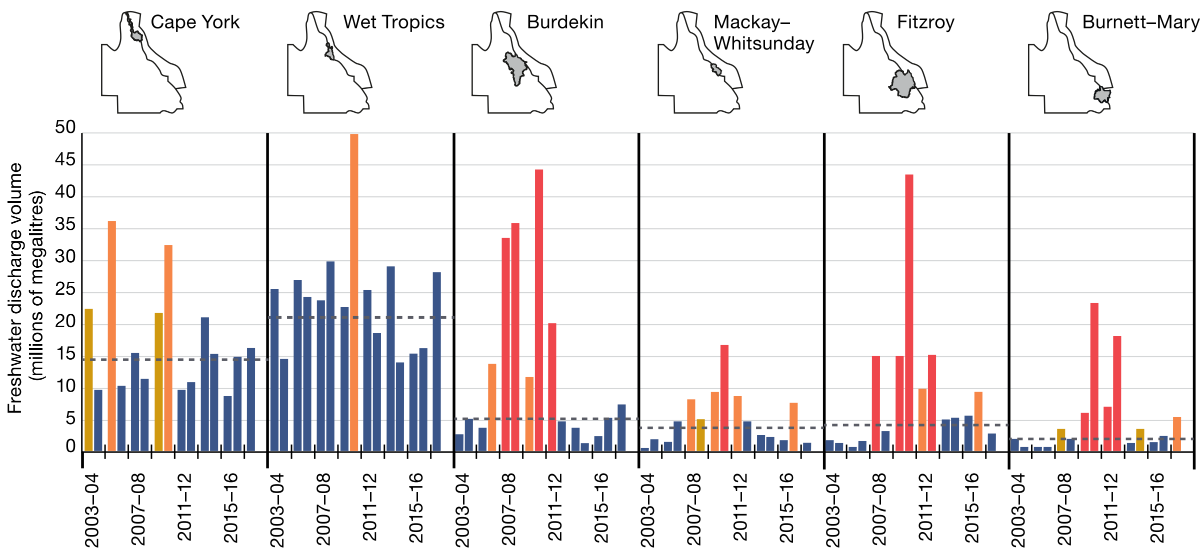

Figure 3.3 Annual freshwater discharge from major rivers, 2003–04 to 2016–17
Discharge in millions of megalitres (ML) (hydrological year: 1 October to 30 September) for the 35 main Reef rivers, combined for each of the six NRM regions. Bar colours: red = ≥3 times long-term median flow, orange = 2–3 times, yellow = 1.5–2 times, blue = <1.5 times. Dashed grey line indicates long-term median for each natural resource management region. Source: Data supplied by Department of Science, Information Technology and Innovation (Qld) 2018. Compiled by James Cook University (Gruber *et al*. 2019[155])

BOX 2

Freshwater inflow — 2019 event

In February 2019, an active monsoon trough led to extreme rainfall and subsequent flooding around Townsville (approximately 1.3 metres of rain fell in 10 days).[464] Heavy rainfalls occurred from Cape York to the Mackay–Whitsunday natural resource management region. The volume of water discharged from the Burdekin River was the largest in eight years (14.5 million megalitres in three weeks), and it extended to the outer-shelf reefs.[465] Greenish waters, indicating high phytoplankton (algae) levels, were observed in mid-February. The flood plume extended beyond the outer shelf and moved south (potentially being carried by the East Australian Current).[465] The flooding is likely to have affected water quality via reduced salinity and elevated nutrient and sediment loads from major river systems, with consequent impacts on seagrass meadows, crown-of-thorns starfish larvae and coral reef ecosystems.[465] Freshwater bleaching and disease may have occurred on some inshore reefs.[465]

Left: Burdekin River flood plume inundates Old Reef, Stanley and Darley reefs. © Queensland and Australian Government agencies/programs: TropWATER (JCU), Marine Monitoring Program (GBRMPA), Office of the Great Barrier Reef, NQ Dry Tropics, CSIRO and NESP (Tropical Water Quality Hub), photographer: Matt Curnock, 2019.
Right: River flood emerging from the Burdekin River (12 February 2019) after unprecedented levels of rain and flooding. The use of imagery from the NASA Worldview application (https://worldview.earthdata.nasa.gov/), part of the NASA Earth Observing System Data and Information System (EOSDIS) is acknowledged.

3.2.4 Sediment exposure

The process of sediment exposure includes the transport of sediment into and throughout the Region, including through resuspension and increased turbidity, and sediment settling on plants and animals. The inflow, dispersion, resuspension and consolidation of sediments from land to the sea is a natural process that has occurred in the Region since the current sea level was reached about 6500 years ago.[85,154,466]

Sediment loads continue to contribute to the poor state of many inshore coastal and marine ecosystems

Since European settlement, suspended sediments entering the Reef lagoon are estimated to have increased five-fold[154,467], which can be largely attributed to human influences.[43] This increase is a result of soil erosion from rangeland grazing and cropping, urban development, deforestation and mining. Some of the increase can also be attributed to fluctuation in weather, climate change and associated changes in rainfall and land-based run-off.[467,468]

Most sediment is delivered to the Region during flood events[469], with the amount varying along the coast between the six NRM regions and individual catchments.[467] Modelling of land-derived total suspended solids indicate that the highest exposure levels from anthropogenic sediment loads are concentrated in the inshore areas, with the largest inputs from the Burdekin River (Figure 3.4).

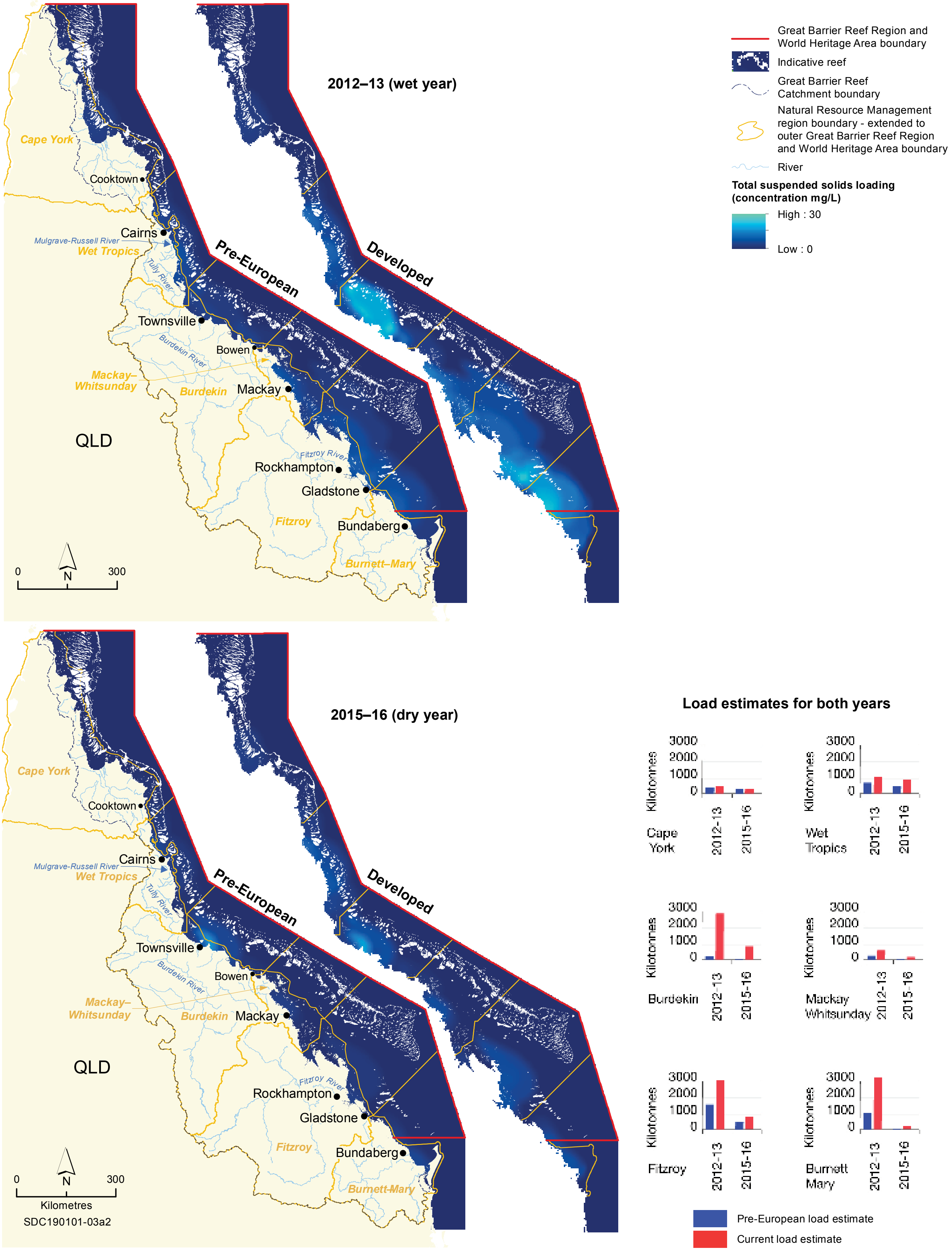

Figure 3.4 Modelled total suspended solids catchment loads, 2012–13 and 2015–16

Modelled distribution of total suspended solids in end-of-catchment loads, based on annual average pre-European (left) and current (right) years, highlighting the difference between a wet year (2012–13 top) and a dry year (2015–16 bottom). The graphs show the modelled annual average loads for each period for the six natural resource management region. The blue bars are pre-development and red bars are current.

Source: Based on the Marine Monitoring Program, compiled by James Cook University (Gruber *et al.* 2019[155])

Most sediments delivered from flood plumes settle relatively close to river mouths (within 50 metres).[470,471] However, fine sediment (smaller than 16 micrometres) is more likely to be carried in suspension and reach the inshore and mid-shelf areas of the Reef.[467,472] Fine sediment can be resuspended by wind and strong tidal currents in shallow waters, and may persist in the water column for at least six to eight months following river input, with the potential to be transported large distances, including to the outer shelf.[43,153,158,467,473,474] Delivery and resuspension of new sediments and resuspension of historic sediments can combine to affect water quality condition all year round.[467,471,475] Sediment exposure can result in the degradation of coral reefs, seagrass meadows and freshwater wetlands, as well as affecting filter feeders and fish.[43,153,473,476,477,478] Specifically, sediment exposure can lead to physical disturbance, burying of organisms and increased susceptibility to disease.[43]

Wet season river influence from 2013–14 to 2017–18 rarely extended seaward of inshore waters.[155] Therefore, impacts to mid-shelf and offshore ecosystems from land-derived sediment exposure during this period were low.[43,469] However, sediment exposure was still significantly higher than pre-European settlement levels, despite low rainfall in the last five years. Across the Region, the relative influence of sediments sourced from river discharge compared to resuspension of sediments pre-existing in the ecosystem remains poorly understood.[469] There have been substantial changes in sediment exposure since European settlement and these changes are significantly affecting inshore coral and seagrass habitats. Overall, the process of sediment exposure has deteriorated in the Region.

3.2.5 Sea level

Sea level in the Region reached its current level about 6500 years ago.[85] Although tides and weather patterns cause local temporal and spatial sea level variation, global sea level is primarily driven by two main processes: thermal expansion (an increase in the volume of sea water as it warms) and increased melting of land-based ice.[479,480] Fluctuations in sea level have played a major role in the evolution of the modern Reef by influencing light availability (a function of water depth), which is the primary driver of photosynthesis and enhanced calcification.[481] Sea level also affects the distribution and functioning of tidal habitats, such as mangroves and low-lying freshwater habitats, due to its strong influence on salinity levels.[482]

Sea-level rise in the Region is increasing faster than the global average

By 2018, global sea level was 82 millimetres above the 1993 average, the highest annual average since systematic monitoring began at a global scale.[452] There is a lag in the response of sea-level rise to global warming.[483,484] Thus global sea-level rise is accelerating as the ocean north continues to warm.[485] Australian sea levels are rising, with the greatest increases being recorded in the northwest, north and southeast (Figure 3.5).[486] Since 1993, the average rate of sea-level rise in the Region was between five and seven millimetres per year[486], well above the global average of 3.3 millimetres per year.[480] Limiting future temperature increases will slow the rate of sea-level rise and provide more options for species and coastal communities to adapt.[487]

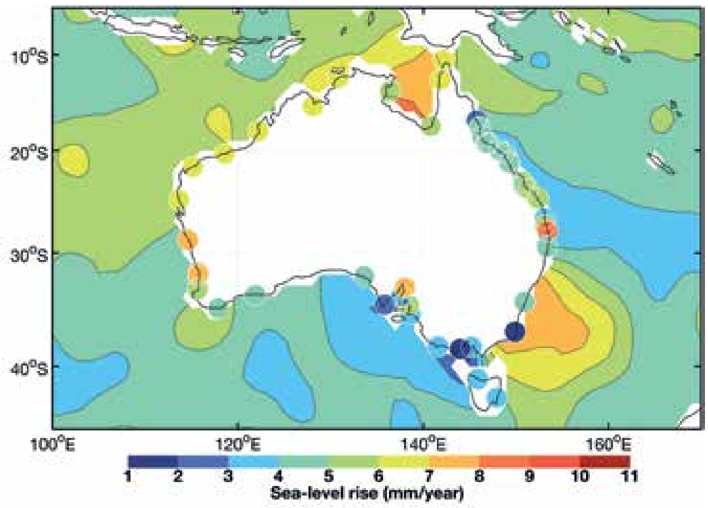

Figure 3.5 Sea level trend annual increase, 1993–2017
Linear trends from January 1993 to December 2017 for the Australian region from the satellite-altimeter data (contours), overlaid with estimates from the tide gauges (coloured dots). Both datasets show the largest sea-level rises occurring in the north and north-west and the lowest rises occurring along the east coast of Australia between latitude 20° south (Bowen) and 35° south (Nora).
Source: White *et al.* 2014[486] and CSIRO 2018[452]

Sea-level rise may reduce coastal protection through the loss of areas of key habitats, such as coral reefs. Although current sea-level rise poses little risk to the Region's coral reefs, future projected sea-level rise may exceed coral reef growth capacity.[488] Increased salinity from sea-level rise may lead to changes in the species composition of wetland communities and their ecosystem functions.[489] While some ecosystems (for example, mangrove forests and seagrass meadows) may be able to move shoreward as sea levels increase, coastal development often curtails these opportunities.[490] Small islands and cays are at risk of inundation and erosion from sea-level rise[491,492,493], directly threatening marine turtles, crocodiles and birds relying on those islands for nesting and roosting.[494,495,496,497] Reef tourism and recreational use of low-lying areas will also be affected given sea-level rise will continue long after emissions of greenhouse gases have stopped.[498]

Sea-level rise is continuous and small increases have occurred since 2014. Although this process is slowly deteriorating, impacts on the Region have not yet been detected.

3.2.6 Sea temperature

The temperature of the surface layers of the ocean is affected by both regional and global-scale processes. On a regional scale, sea temperature is influenced by seasonal variations in solar energy, cloud cover, currents, surface winds and the tidal regime. Globally, large-scale climate drivers include the El Niño–Southern Oscillation and anthropogenic heating. The world's oceans also play a major role in climate by absorbing surplus heat and energy.[499] Oceans have absorbed more than 90 per cent of the extra heat trapped by increased greenhouse gases since the 1970s.[500] As a result, the ocean is warming at an unprecedented rate.[501,502,503]

Sea temperature influences the distribution, survival, reproduction, growth, physiology and productivity of marine organisms.[377,504,505] Most marine animals are ectotherms, unable to heat and cool their body. Therefore, sea temperature determines their body temperature, and any changes can alter their distribution, metabolism, respiration and behaviour.[504,505] Temperature also affects marine organisms by altering other water properties; higher sea temperatures limit the concentration of dissolved oxygen available for respiration[506] and increase the solubility and toxicity of some heavy metals.[507] Temperature is also important in regulating the rate of coral calcification[508,509] and the productivity of seagrasses and mangroves.[510] Therefore, extremes in sea surface temperatures can reduce fitness and cause mass mortality of sensitive organisms.[91,99,141]

Record high sea temperatures have occurred in the past four years with widespread, severe impacts on species and habitats

Corals are particularly sensitive to small changes in temperature because of their narrow thermal tolerance range (Section 2.4.4).[511] Thermal stress of just one degree Celsius above the long-term summer maximum temperature for a few weeks can cause reef-building corals to eject the algae that live in their tissue, a process known as coral bleaching.

Above-average annual sea surface temperatures have been observed for the Reef every year since 2012, and present day temperatures of Reef waters are approximately 0.8 degrees Celsius warmer than when records began (Figure 3.6). The Region's sea temperatures were the warmest on record in 2016 (1.03 degrees Celsius above the 1961–1990 average, Figure 3.6), part of a long-lasting marine heatwave[512] that resulted in a severe mass bleaching event.[90] When unusually warm summer sea temperatures occurred again in 2017, a second mass bleaching event affected the Region. This was the first back-to-back bleaching event ever recorded on the Reef, and it caused widespread mortality of shallow-water corals (Section 2.3.5).[141]

There have been ongoing, substantial increases in sea temperature across most of the Region due to climate change, indicating deterioration of sea temperature processes since 2014.

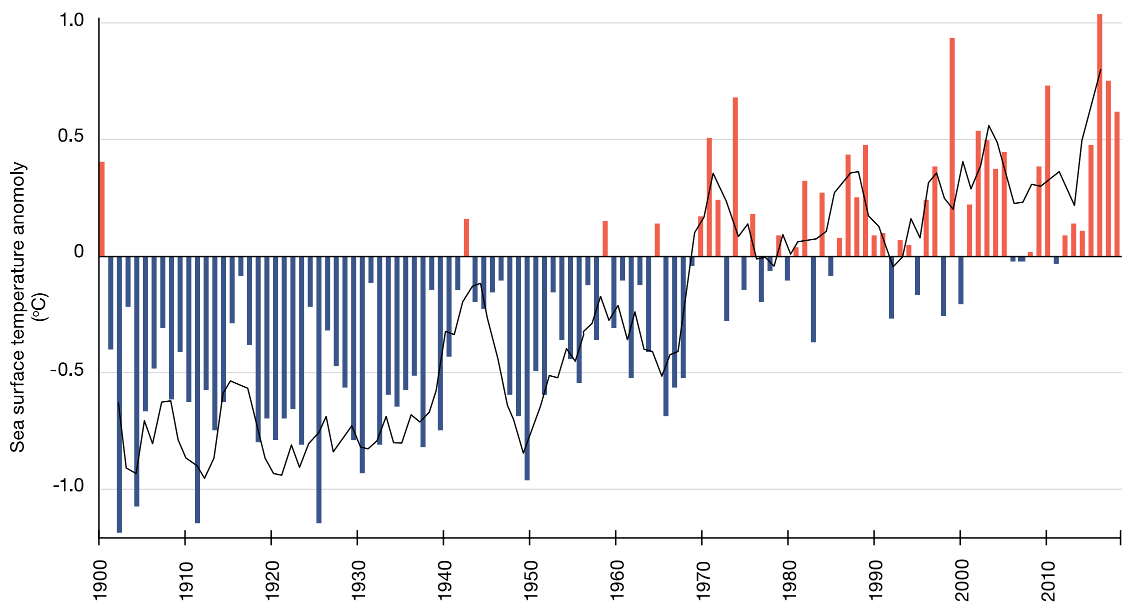

Figure 3.6 Sea surface temperature anomalies for Great Barrier Reef waters, 1900–2018
Above-average annual sea surface temperatures have been observed for the Region every year between 2012 and the present, and have been persistently high for the past two decades. Anomalies are the departures from the 1961–1990 standard averaging period. Black line indicates a five year running average. Source: Australian Bureau of Meteorology 2019[513]

3.2.7 Light

Light availability in the marine environment is variable and governed by a combination of suspended sediment, cloud cover and the optical properties of water, which bends and absorbs light waves. The rate at which light decreases in the water column is determined by water depth and turbidity, which is a measure of the degree to which the water loses its transparency due to the presence of suspended particles.[514] In clear water, such as the open ocean, light may penetrate down to 200 metres. However, inshore waters typically contain particles that scatter light and affect its transmission. These particles can originate from naturally occurring sediments or as a result of direct or indirect human activities (Section 3.2.4).

Light availability in the inshore areas has decreased over the past decade

Light is an important determinant of the distribution, growth, depth range and productivity of organisms reliant upon photosynthesis, including seagrasses, phytoplankton and corals.[70,200,515] Water quality affects light reaching seagrass meadows, and light in turn controls the productivity, abundance and distribution of seagrasses.[516,517] Reduced light, coupled with recent warmer sea temperatures, has probably hampered seagrass recovery.[74] For visual predators, light influences prey visibility and affects the energy needed to search and acquire food.[518] Exposure to light plays a key role in coral ecology, affecting settlement[519,520], direction of growth[521], competition with other organisms[522], calcification rates[515], and susceptibility to thermal stress and disease.[523,524,525] Light also affects the dispersal, settlement, feeding and mating patterns of fish and invertebrates.[526]

Light availability within the Region is affected by seasonal rainfall, weather and activities that resuspend sediments (currents, winds, tides, land-based run-off, anchoring and dredging). Turbidity of inshore waters in the Region, which has been measured since 2007[527], has shown a general increase over the past decade, resulting in an overall deterioration of the process of light availability (Sections 3.2.4 and 6.5)[460] and an overall deterioration of this process of light availability.

Light penetrating the surface waters above a shallow reef. © Matt Curnock

3.3 Current condition and trends of chemical processes

Three chemical processes are graded. Ocean pH and ocean salinity remain in good condition and nutrient cycling continues to be graded as poor.

↔

Full assessment summary: see Section 3.7.2

3.3.1 Nutrient cycling

Nutrients are essential for the growth and survival of organisms. Nutrient cycling is one of the most important ecosystem processes, transferring nutrients from the physical environment through uptake by organisms, passing them through food chains, and returning them to the physical environment when organisms decay or die. Nitrogen, phosphorus and carbon are the main nutrient cycles in the marine environment.[528,529] Marine microbes (Section 2.4.6) play an important role in the ocean's nutrient cycle by decomposing organic matter.[530,531] This ongoing cycling of nutrients by microorganisms is critical for sustaining productivity in the marine environment.[532] Within the Region, the nutrient cycle is critical for the persistence of most organisms, particularly corals.[533] Concentrations of nutrients, such as nitrogen and phosphorus are naturally low in the open ocean.

Most southern inshore areas of the Region are exposed to elevated nutrient concentrations, particularly during the wet season

The anthropogenic load of dissolved inorganic nitrogen discharged from the Catchment since 2012 has been generally lower than the previous five years.[155] While small improvements in land management practices to reduce dissolved inorganic nitrogen inputs have been reported[43,463], the observed reduction in loads over this period can mostly be attributed to reduced flow [460,469] (Section 6.5).

Nutrient loads in the Region have noticeably increased since European settlement in the adjacent Catchment (Figure 3.7). Modelling of land-derived dissolved inorganic nitrogen indicates that the highest exposure levels are concentrated in inshore areas, with higher contributions from the Wet Tropics region in both wet and dry years compared with other NRM regions (Figure 3.7). The influence of land-based dissolved inorganic nitrogen extends to mid-shelf areas from the Catchment in wetter years, such as 2012–13 (Figure 3.7). The Fitzroy and Burnett–Mary regions are not monitored frequently enough to assess trends.[460,469]

The multi-year trends of concentration of dissolved inorganic nitrogen vary across the Region.[155] Dissolved organic carbon increased sharply in all monitored regions since monitoring began in 2005.[460,469] Dissolved organic carbon drives microbial growth and promotes a higher incidence of coral diseases.[534] High concentrations of dissolved inorganic and organic carbon may lead, in the longer term, to reduced growth of reefs, loss of substrate and reef erosion.[535]

Land-derived nutrient inputs to the Region largely occur during the wet season[536], with most dissolved nutrients being rapidly taken up biologically or bound chemically onto particles in the ocean. Excess dissolved inorganic nitrogen poses the greatest risk to the Region because it is readily taken up by phytoplankton and microalgae, causing an imbalance in the system.[43,537] In years of large river flow, these nutrients can be transported large distances.[43,458,537]

The increase in nutrient loads during flood events can exacerbate the spread and persistence of crown-of-thorns starfish larvae, which feed on phytoplankton that thrive on dissolved nutrients (Section 3.6.2).[193,538] Higher nutrient levels also increase the susceptibility of corals to disease and thermal stress[539,540], affect coral reproduction[514], reduce light for seagrass and corals[184,514], and promote fleshy macroalgal growth in some areas.[43,461,541] Although considered stable, there have been substantial changes to nutrient cycling occurring since European settlement, affecting inshore ecosystems, especially seagrasses and corals.

Algae overgrowing a branching coral. © GBRMPA 2016, photographer: Jessica Stella

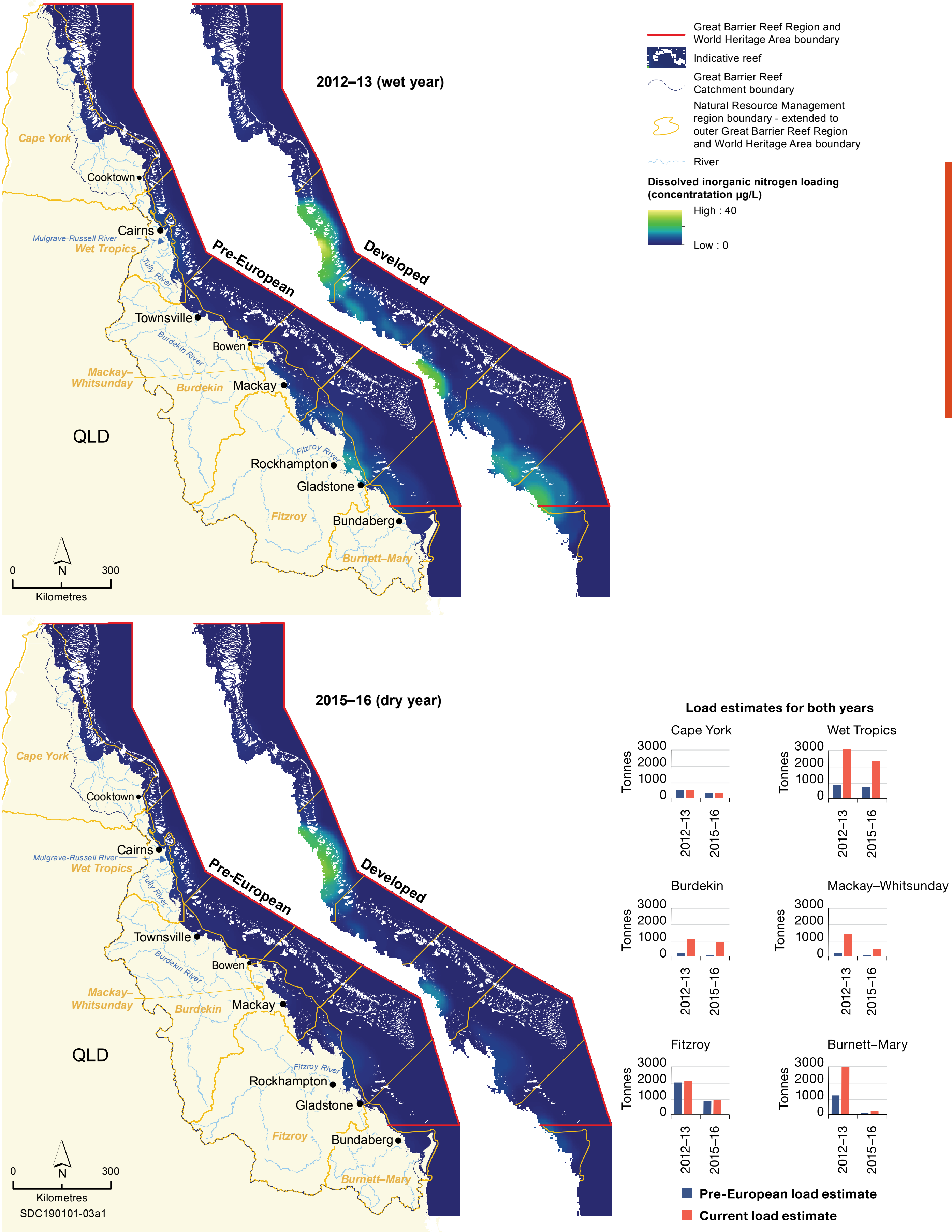

Figure 3.7 Modelled dissolved inorganic nitrogen catchment loads, 2012–13 and 2015–16

Modelled distribution of dissolved inorganic nitrogen end-of-catchment loads, based on annual average pre-European (left) and current (right) years, highlighting the difference between a wet year (2012–13 top) and a dry year (2015–16 bottom). The graphs show the modelled annual average loads for each period for the six natural resource management regions. The blue bars are pre-development and red bars are current.

Source: Based on the Marine Monitoring Program, complied by James Cook University (Gruber *et al.* 2019[155])

3.3.2 Ocean pH

Ocean acidification is often expressed in terms of the pH of seawater. It is measured on a scale from zero to 14, with values below seven considered acidic and values above seven considered basic. The baseline pH of the oceans is a slightly basic 8.2.[542,543] The largest driver of increased acidity of seawater is emissions of carbon dioxide into the atmosphere, causing increased dissolved carbon dioxide in the ocean. Although carbon dioxide is a major component of the carbon cycle, the proportion of carbon dioxide in the atmosphere is increasing as a result of human activities, predominantly burning of fossil fuels.[544,545]

The ongoing decrease in ocean pH will reduce calcification, making coral reefs more vulnerable to intensifying storms

The ocean has already absorbed approximately 30 per cent of the atmospheric carbon dioxide that has originated from human activities, lowering the pH by approximately 0.1 pH unit.[545] This uptake reduces the seawater concentration of carbonate ions, which are required by most organisms that build shells, including corals and shellfish.[546] The potential and actual effects of ocean acidification on marine organisms has become better understood in the past 15 years.[547] Experimental studies have identified impacts, including altered survival, calcification, growth, development and abundance of a broad range of reef organisms[548], including fish[549], phytoplankton[550,551], marine plants[552,553,554], corals[555], microbes[254] and other reef invertebrates.[556,557] Crustose coralline algae, which provide important surfaces for coral settlement, appear to be particularly sensitive to increases in ocean acidity[202,558]; hence, coral recruitment rates could be adversely affected as the ocean acidifies.[559,560,561]

Perhaps the largest risk from ocean acidification is a change in the net rate of calcium carbonate accretion (the deposition of calcium carbonate by calcifying organisms). For reefs to grow, net accretion must be higher than net dissolution. Reduced calcification can result in coral skeletons being more brittle and at greater risk of breakage from strong waves.[562] Changes to ocean pH are having, and are likely to continue to have, fundamental and substantial impacts on a wide variety of organisms.[487]

Current ocean pH varies within the Region, exhibiting a cross-shelf gradient. On mid and outer-shelf reefs, the partial pressure of carbon dioxide has risen at the same rate as atmospheric values over 30 years. By contrast, values on inshore reefs have increased up to three times faster, due to higher respiration and nutrient levels.[162] Given the small but continuous decreases in ocean pH, the ocean pH process has deteriorated since 2014.

3.3.3 Ocean salinity

Overall, salinity remains stable across most of the Region

Salinity refers to the concentration of salt in a given volume of water, often expressed as parts per thousand. The average salinity of the ocean is 35 parts per thousand (every kilogram of seawater contains 35 grams of salt). Salinity levels can change drastically over the course of a day as a result of rainfall, river flows, evaporation and water movement due to wind, currents and tidal mixing.[563,564] Because seawater is denser than fresh water, salinity can change rapidly with depth during flood events, with low-salinity plumes predominantly remaining on or near the surface while salt water remains deeper.[565] Salinity fluctuates following high-rainfall events or prolonged drought.

Salinity within the Region has remained at 35 parts per thousand.[460,566] Reefs closest to the coast, such as those off Cape York and the Wet Tropics, are subject to more regular low-salinity inflows.[565]

Low salinity associated with floodwaters can cause extensive mortality of a range of Reef species, including corals, crustaceans, molluscs, sponges, fishes and seagrasses.[458,567,568] Low salinity can also have sub-lethal effects on Reef organisms, such as reduced coral growth rates[569] and reduced seagrass flowering in response to physiological stress.[567] Combined pressures from lower salinity and higher water temperatures can also have a significant effect on organisms. For example, blooms of dinoflagelates (plankton) can be triggered, leading to increased frequencies of ciguatera fish poisoning.[570] Changes in salinity have largely been a result of freshwater inflow, affecting the condition of inshore areas. Overall, the ocean salinity process is considered stable across most of the Region.

3.4 Current condition and trends of ecological processes

Ten ecological processes are graded. Primary production remains in very good condition, and five processes (microbial processes, particle feeding, herbivory, competition and connectivity) remain in good condition. Predation and recruitment continue to be graded as poor, whereas symbiosis and reef building have deteriorated to a poor grade.

↓

Full assessment summary: see Section 3.7.3

3.4.1 Microbial processes

Microbes play a significant role in cycling carbon and nitrogen, largely through the decomposition of organic matter[571], and are important vectors of disease. Microbial processes are critical for regulating the composition of the atmosphere, influencing the climate, recycling nutrients and decomposing pollutants.[572] Despite their importance, most microbial processes remain poorly understood, particularly in the marine environment.[573]

Microbial processes are often the unseen driver in ecosystem processes.[574,575] As the basis of the marine food chain, microbes convert dissolved nutrients into plankton biomass[259], which supports the marine food web. Microbial communities can influence the health of other organisms through important symbiotic relationships. For example, beneficial microbes that cycle nitrogen may be central to the stability of the coral–algae symbiosis by influencing the growth and density of the *algae symbiont zooxanthellae*.[533,576] Harmful microbes (pathogens) can affect the health of corals, sponges, seagrasses and other organisms, causing disease and mortality.[576,577] Over-abundance of harmful microbes in the ecosystem has been linked to stressors, such as overfishing, exposure to elevated nutrient concentrations and increased temperatures.[573,578,579] Pathogenic microbes carried by plastic pollution can promote disease when in contact with coral.[580]

Although critically important to ecosystem health, the status of most microbial processes remains poorly understood

Information on the status of most microbial processes in the Region, one of the main drivers underpinning ecosystem function, is limited and represents a large knowledge gap. Diseases were observed in coral trout and corals in areas of the Region affected by temperature extremes in 2016 and 2017 (Section 3.6.1). However, the impact of this across the entire Region has not been quantified. Increases in fleshy macoalgae can occur during times of elevated nutrient concentrations (Section 2.4.3), due to an over-abundance of bacterial communities that thrive in high nutrient environments.[581] Seagrass meadows reduce the relative abundance of disease-causing bacteria (by up to 50 per cent), indicating seagrass ecosystems may play an important role in regulating harmful microbial processes in the Region.[58] Although some spikes in disease have occurred for some species, no clear trend is apparent for the Region's microbial processes.

3.4.2 Particle feeding

Particle feeders encompass a broad group of animals, including filter, suspension and deposit feeders that consume particulate matter. These animals include sea cucumbers, feather stars, fishes, corals, molluscs, sponges and worms. Particle feeding supports the ecosystem's nutrient cycle (Section 3.3.1), cleans large quantities of water and sediment by filtering out particles, bacteria, algae and zooplankton, and links the benthic and pelagic environments.[582,583,584] Particle feeders can exert a considerable influence on the ecosystem. For example, giant clams (*Tridacna gigas*) can filter large volumes of water, reducing the amount of nutrients in the water column.[585,586]

The process of particle feeding is likely to have deteriorated

Although extensive information is available on trends in the abundance of corals, it is difficult to quantify the current condition and trend of this process as a whole, given information on other particle feeders (such as sponges and echinoderms) is limited.

Suspended sediments and nutrients in the water column can harm particle feeders, such as sponges, by clogging the filtration apparatus and hindering feeding. Since 2014, inshore areas in the Region have continued to experience repeated and elevated levels of nutrients[155]; therefore, it is likely that particle feeding in these areas has declined. In addition, following bleaching events in 2016 and 2017, filter feeding corals have decreased in abundance to the lowest levels ever recorded.[88] It is likely that particle-feeding fish[273], which rely heavily on coral habitats for shelter, have also decreased since 2016. However, coral reef sponges, which are more resilient to environmental stressors than corals[587], are assumed to be less affected by recent impacts.

Overall, there have been some significant changes in particle feeding in some areas as a result of high nutrient levels and thermal stress events in 2016 and 2017. As a result, the condition of particle feeding as a process has deteriorated.

3.4.3 Primary production

Primary production and photosynthesis are closely linked to the availability of light and concentrations of available inorganic nutrients and generally occur in the upper water column at depths of less than 100 metres. Nitrogen and phosphorus sources play a significant role in determining the rate of primary production.[588,589,590] Land-based run-off, inflow from the Coral Sea, upwelling and resuspension all support productivity within phytoplankton communities.[424,591]

In the Region, primary producers include phytoplankton, mangroves, seagrasses, benthic algae and symbiotic algae in the tissues of Reef organisms, especially corals. In lieu of direct measurements of primary production, a higher abundance of primary producers can be used as a proxy to indicate overall condition. Chlorophyll-*a* is often used as a proxy for estimating phytoplankton biomass.[592] Frequent phytoplankton blooms and associated higher primary production occurs during the wet season when more nutrients are available.[593] Primary production is higher in inshore areas (except Cape York) due to year-round elevated nutrient loads.[155] The extent and condition of seagrasses have generally increased since 2014, which may have enhanced their primary production in the Region, although abundance has declined slightly since 2015–16 (Section 2.4.2).[74] Mangroves have remained relatively stable within the Region (Section 2.4.1) and benthic algae have generally increased in abundance at disturbed sites (Section 2.4.)[193,594], potentially increasing primary production in these areas. Following the bleaching events in 2016 and 2017, it can be assumed that primary production from coral–algae symbioses has reduced as a result of coral mass mortality, particularly in the northern two thirds of the Region. Overall, the condition of primary production is variable, with no consistent trend.

3.4.4 Herbivory

Herbivorous fish and green turtles avoid sediment-laden turf algae

Herbivory is the removal and consumption of plant matter, which provides nutrition for the consumer and shapes the location and health of the plant matter.[595] Herbivory includes removal of plant matter by large herbivores (such as green turtles and dugongs) and cropping, grazing and excavation of algae, which is performed predominantly by herbivorous fish (over 178 species)[596] and to a lesser extent by molluscs, echinoderms and crustaceans.

The process of herbivory supports nutrient cycling and can facilitate dispersal of seagrass species[65] (Section 8.3.6). Following disturbance, herbivory plays an important role in reef recovery.[597] However, coral replenishment and herbivory can be overcome when macroalgae get too dense and form underwater forests[419,598] (Section 2.4.4). Herbivores can be deterred from entering and feeding on algal forests due to fear of predation[598], resulting in less herbivory and further expansion of a macroalgal-dominated state.[599]

Having a number of herbivorous species that can fulfil a range of ecological roles provides a level of 'insurance' for the ecosystem, and can increase recovery capacity following disturbance (Figure 3.8). Benthic turf algae are usually the first species to establish or regrow after a disturbance, and there is a diverse group of herbivores (both fish and invertebrates) that feed on this type of algae. Grazing fish differ in their feeding behaviour (for example, in their ability to remove algae from specific key microhabitats across the Reef).[600] By contrast, few fish species can effectively remove larger fleshy macroalgae. In the northern Reef, large fleshy macroalgae are removed by one key species, the unicorn fish, which is responsible for approximately 90 per cent of macroalgal removal.[418]

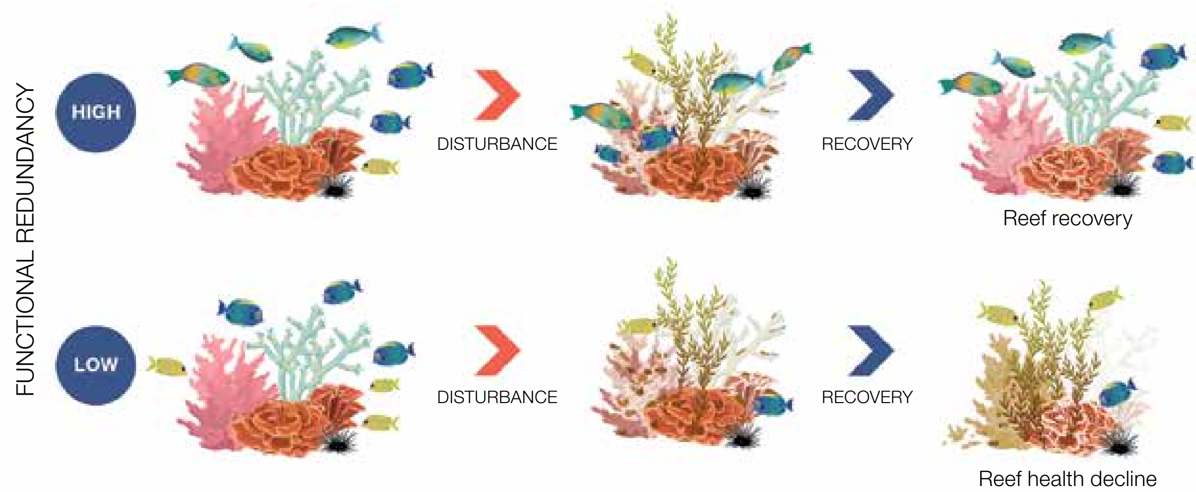

Figure 3.8 Herbivore functional redundancy
Reefs with high functional redundancy (top) have a higher number of animals that perform important functions, such as algal removal, which helps reefs recover faster following disturbance. Reefs with low functional redundancy (bottom) have less capacity to respond to, and recovery from, disturbances. Source: Adapted from Nash *et al.* 2016[601]

Fish herbivore abundance is generally higher on offshore and mid-shelf locations, with reef exposure (to wave energy and other factors) greatly affecting food availability and fish size.[602] The process of herbivory is not regularly monitored across the Region and remains a knowledge gap. However, the presence of herbivores can provide some indication of potential herbivory rates. Long-term monitoring of herbivorous parrotfish and surgeonfish (Section 2.4.7) indicate that abundances across the Region have generally remained stable, with some variability cross-shelf (Section 2.4.7, Figure 2.12). Offshore locations have the greatest variability since 2016–17, with parrotfish increasing five-fold offshore Cairns and surgeonfish decreasing by half offshore Townsville. Elsewhere, on inshore and mid-shelf locations, parrotfish and surgeonfish abundance has generally remained stable since 2009, with the exception of the Pompey Complex reefs, where parrotfish declined by half between 2009 and 2014.[282] At two southern locations, where 2018–19 surveys were completed, parrotfish and surgeonfish declined in abundance around the Swain Reefs. Whereas on offshore reefs around the Capricorn Bunker group, parrotfish abundance increased by approximately 40 per cent.[282]

On a smaller scale within reefs, many factors (including sediment load and particle size) combine to influence the location of herbivory. For example, some parrotfish avoid feeding on algal surfaces coated with poor-quality coarse sediments.[603] Following cyclone Yasi in 2011, large increases in sediment loads around Orpheus Island led to a dramatic decrease in grazing by herbivorous fish (92 per cent reduction in feeding by rabbitfish).[281] Green turtles were also deterred from feeding on sediment-laden turf algae.[604]

The condition of herbivory as a process across the Region and the mechanisms that affect it are not well understood. There is some variability in herbivory across the Region, but not to the extent of significantly affecting ecosystem function, and overall the condition of this process has remained stable.

3.4.5 Predation

Predation (the process of animals consuming other animals) influences the distribution, abundance, behaviour, fitness and evolution of prey species.[269,285,605,606] For example, predator abundance can alter prey behaviours, such as wariness and shelter seeking. In turn, predator presence affects prey species' distributions at small scales, leading to changes in other processes (such as reduced rates of herbivory)[607].

Apex predators include large-bodied animals that generally have large home ranges[608], such as large sharks, pelagic fishes (such as trevally and tuna), birds, and some marine mammals and reptiles. Smaller reef sharks are considered middle-order (meso) predators, as are other large predatory fishes (such as coral trout). Meso-predators generally have smaller home ranges than apex predators and feed on smaller prey.[609,610] Predatory fishes have high cultural, social and economic value to recreational, commercial and Indigenous fishers (Section 5.4). They are generally equally spread across the inner, mid and outer-shelf reefs within the Region.[611]

The abundance of reef sharks on the outer-shelf reefs varies, with significantly higher abundance and diversity occurring on deeper reef slope habitats.[612] The 2009 and 2014 Outlook Reports noted reef shark and coral trout abundances were depleted by fishing[2,613]; recent research suggests it may take 20–40 years of effective no-entry protection to restore shark population numbers.[297] Analysis of the trend in sharks caught in the shark control program since the 1960s indicates a regional depletion of sharks, particularly large mature individuals.[298,614] Sharks and rays are still considered to be in poor condition overall (Section 2.4.8) due to overfishing, bycatch and poaching.

Trends in long-term abundance of reef-associated predators are variable, with some increases in coral trout occurring in mid-shelf and offshore reefs in the Swain Reefs since 2012.[611] Whereas other meso-predators (labrids and lethrinids) declined.[611] Offshore Townsville (around Magnetic Island and the Palm islands), the population density of coral trout halved between 2007 and 2012[615]; and although gradual increases have occurred since then, they have not yet returned to the higher densities recorded prior to 2007.[615]

The key drivers and threats affecting predation include climate change, habitat loss and fishing.[361,611,616,617] All of these drivers are increasing. Predation is likely to decrease further in the Region as a result of both bottom-up effects (such as decreases in availability of habitat and prey for seabirds) and top-down effects (such as fishing) (Section 8.3.4). A growing body of research demonstrates that well-managed no-take zones effectively protect predatory fishes and sharks over small and large scales.[618,619,620] These trends may change if habitat structure declines, particularly for coral trout, which are dependent on habitat complexity (Section 8.3.4).[210,621,622]

The overall level of change in the process of predation since 2014 is not clear. While recovery is occurring for some predators in some locations, concerns remain for others.

3.4.6 Symbiosis

The high occurrence of symbiotic relationships in the Region is one of the biggest drivers of biodiversity

Symbiosis is a close ecological relationship between at least two different species. This relationship can be beneficial to all participants (mutualism), beneficial to one participant and harmless to the other (commensalism), harmful to one participant while not benefiting the other (amensalism) and beneficial to one and harmful to the other (mainly parasitism). Symbioses develop over long evolutionary timeframes, maintained by natural selection, and have been a major driver in the formation of new species.[623,624] Many symbionts are keystone species; these are usually inconspicuous, smaller organisms that have a disproportionately significant impact on the greater biodiversity of the ecosystem.[625] Symbioses usually, but not always, involve strong interdependencies.[626] They enable species to obtain resources that would otherwise be unobtainable and are, therefore, a critical ecological process.

Within the Region, the coral–zooxanthellae and clownfish–anemone relationships are perhaps the best known examples of symbioses. Other important symbiotic relationships include coral guard crabs (*Trapezia* species) that live within *Pocillopora* corals and clean[627] and defend their coral hosts.[628,629,630] An estimated 40 per cent of known species are parasitic symbionts[631,632], and approximately 75 per cent of the links in food webs involve a parasitic species.[633] The loss of any one of these symbiotic interactions may have unforeseen and serious consequences for ecosystem function.

Figure 3.9 Clownfish in a bleached anemone
The clownfish (Amphiprion percula) nestled within a bleached host anemone during the 2016 marine heatwave on the Great Barrier Reef.
© GBRMPA 2016, photographer: Jessica Stella

Symbioses are particularly susceptible to disturbances, since a direct impact on one symbiont will affect the other.[83,634] Environmental changes, such as thermal stress due to climate change, have the potential to alter the nature of symbioses (for example, changing a mutualistic relationship to a parasitic[635] or competitive one[636]). Bleaching of a symbiont's host, such as coral and anemones, has negative effects on the fitness and survival of the symbiotic animals that rely on them, such as coral crabs[243,636] and anemonefish.[637,638] Due to the strong inter-dependencies common between symbiotic partners, symbiont abundance and distribution can be used as a proxy for the condition and trend of symbiosis in the Region.

Based on the unprecedented decline of hard coral cover and changes in coral community composition following mass bleaching in 2016 and 2017[91], it is highly likely that symbioses involving coral have significantly deteriorated.[243,637] Anemones were also susceptible to severe bleaching (Figure 3.9) and mortality, resulting in a subsequent loss of anemonefish.[243,637] Observations of severe bleaching in other habitat-forming species, such as giant clams, probably resulted in a decline of symbiotic species. The recent decline of fish diversity and reduction in abundance of some species[273] will also affect associated symbioses. As a result, the condition of this process has deteriorated since 2014.

3.4.7 Recruitment

Recruitment has declined sharply to the lowest levels recorded for many key species

Recruitment is a process by which new individuals are added to an existing population. Successful recruitment relies on sufficient individuals surviving through various life history stages to become part of the reproductive population.[639,640] The process of recruitment is one of the key ways in which depleted populations are replenished (Figure 3.10).[641] New recruits can either be sourced locally (self-seeding within the same reef) or from afar (larvae carried by currents). Generally, self-seeding populations (such as brooding corals) have relatively low connectivity, while populations that disperse over greater distances (such as spawning corals) have relatively high connectivity (Section 3.4.10).[642]

The condition of recruitment across the Region is only well known for some species. The natural replacement of corals after a disturbance relies on successful recruitment of new individuals. Since 2014, inshore juvenile coral densities (an indicator of recruitment and subsequent survival) have generally declined in the Wet Tropics, Burdekin and Mackay–Whitsunday regions.[440] The density of juvenile corals remains low in the Fitzroy region due to prevalence of macroalgae suppressing recruitment and a decline in settlement of coral larvae.[193]

In 2018, coral larval recruitment, averaged across the Region, declined by 89 per cent compared with historical levels (Figure 3.11).[96] The loss of adult coral brood stock after the mass bleaching events was the dominant driver of this widespread and unprecedented decline in recruitment (Section 8.3.1).[96] The southern region, which escaped severe bleaching in 2016 and 2017[88,141], had higher recruitment in 2018 compared with historical levels.[96]

Figure 3.10 Recruitment can be complex, relying on many different habitats and processes

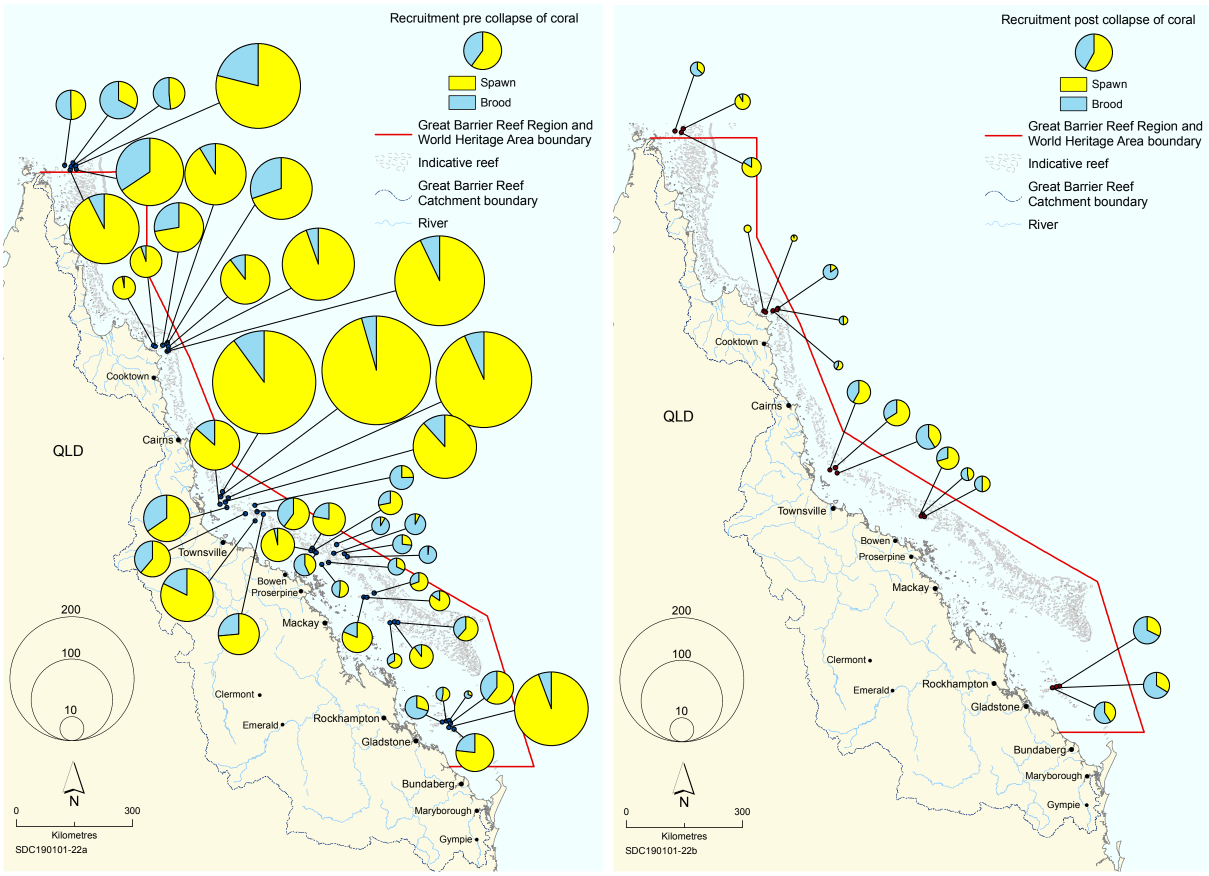

Figure 3.11 Coral recruitment along the 2300 km length of the Reef before and after consecutive mass bleaching events in 2016 and 2017

Left: Average density of recruits (mean number of settled coral larvae per sampling panel on each reef), measured over three decades, from 1996 to 2016 (sample size of 47 reefs, 1784 panels).

Right: Density of recruits after mass mortality of corals in 2016 and 2017 due to back-to-back bleaching events (sample size of 17 reefs, 977 panels). Yellow and blue indicate the proportion of spawning and brooding coral species, respectively. The size of each circle represents the overall recruit density for spawners and brooders combined. Source: Hughes *et al.* 2019[96]

Effective no-take and no-entry zones have been shown to produce and export recruits of commercially important fish species (Section 7.3.3 Box 11).[619,643] Most coral reef fish larvae spend days to weeks in the open ocean before settling on coral reefs.[644] Given the strong swimming abilities of larval reef fish[645] and ocean currents, dispersal of reef fishes within the Region can be large. Some reefs can be a source of larvae for other reefs up to 250 kilometres away.[619,646] Alternatively, on some geographically isolated reefs, populations generally rely on self-recruitment.[619,643]

Across the Region there is no long-term monitoring of reef fish recruitment. It is likely that the recent mass mortality of corals in 2016 and 2017 will have reduced the recruitment of fishes that rely on coral as a settlement habitat.[270,440] These temperature extremes may have also reduced the reproductive capability of some adult fish.[504]

Recruitment has decreased for green turtles at Raine Island[647] (Section 2.4.10) and for loggerhead turtles on the Woongarra coast[648] (Section 8.3.5). Feminisation of turtle populations due to global warming is occurring at several northern Reef rookeries (for example, Raine Island and Moulter Cay), which will reduce male recruitment into the Region.[319] Ingestion of marine debris by post-hatchling turtles and pest predation of eggs and hatchlings at nesting areas[649,650] may also reduce marine turtle recruitment.

Breeding populations of six seabird species are declining within the Region[359] (Section 2.4.12). The declines may be attributed to inadequate food supplies due to warming sea surface temperatures.[361] Declining breeding populations directly affect recruitment and the success of future populations.

Substantial changes in recruitment have occurred, significantly affecting a number of species, and overall the condition of the process of recruitment has deteriorated since 2014.

3.4.8 Reef building

Reef building is under increasing threat from mass bleaching of corals and future ocean acidification

Reef building, or the growth of coral reefs, occurs when net accretion of calcium carbonate by calcifying organisms exceeds net erosion.[85,651] Hard coral growth is the primary driver of reef building, contributing up to 75 per cent of the total calcium carbonate.[652] Other calcifiers, such as *Halimeda*, foraminifera and crustose coralline algae, also contribute a significant amount of carbonate sediments to inter-reefal areas and reef-building ‘cement’, consolidating the reef framework.[31,653,654] For example, the northern *Halimeda* banks (Section 2.3.8) are estimated to contain up to four times the calcium carbonate of adjacent coral reefs[653], contributing significantly to the overall carbon budget of the Reef.[655] Rates of calcification are influenced by many factors, such as the abundance of calcifying organisms, light availability[515], sea temperature[508,656] and the concentration of carbonate ion in seawater.[657,658]

Reefs can erode in three ways: mechanical erosion due to waves and currents; bioerosion caused by reef animals, such as boring worms, sponges, crustaceans[584,659,660] and fishes, (for example, the bumphead parrotfish [661]); and dissolution caused by ocean acidification.[562,662] For reef building to remain stable, calcification rates must be greater than the rate of erosion.[656] Within coral reef habitats, any reduction in either live coral tissue or colony growth rates can tip the scale to the side of erosion.[91,163,545]

The contribution of coral to the reef-building process is likely to be higher in the southern areas of the Region where coral cover is moderate.[95] The unprecedented decline in coral in the northern two thirds of the Region since 2016 is likely to have affected its contribution to reef-building processes.[90,91,141] Throughout the Reef, calcification declined by 14 per cent between 1990 and 2005.[508] Increasing sea surface temperatures and ocean acidification have been implicated as the primary drivers contributing to this decline, with the trend expected to continue in the future.[508,663]

The condition of reef building has deteriorated since 2014, largely due to the effects of unprecedented declines in coral cover.

3.4.9 Competition

Competition is the interaction between organisms for the same resource and is one of many processes influencing community structure.[428] When resources are scarce, competitive interactions can increase in frequency, duration and intensity. Since most tropical marine ecosystems have a limited number or abundance of resources, such as space, light, shelter and food, competition for resources can be intense.

Competition for space is evident among many species within coral reef habitats. Of particular importance is the interaction between corals and macroalgae; the balance can be tipped from coral to algal dominance through higher nutrient levels, coral bleaching events, declining coral recruitment and overfishing of herbivorous species.[664]

Availability of suitable habitat and the density of competitors are the main factors mediating competitive interactions between fishes and invertebrates on the Reef.[636,665,666] Loss of coral cover and habitat complexity can affect reef fish diversity and abundance.[667,668] Changes in coral composition, as occurred after the two consecutive mass bleaching events in the Region[91], have affected competition between juvenile coral reef fish by changing their behaviours and interactions.[669] Although the understanding of competitive interactions has improved since 2014, knowledge gaps remain for this complex process.

Decreasing ocean pH could change the balance of coral macroalgae competition in favour of algae, possibly as a result of slower coral growth rates[670] and changes in chemical competitive mechanisms of corals.[671,672] Large reef fish compete for shelter under suitable plating corals.[210,621] However, the significant loss of habitat-forming corals (Section 2.3.5) increases competition for shelter. This may subsequently affect fish fitness and the ecological functions they perform.[622] Changes in environmental variables, such as thermal stress, also increase and alter the frequency or nature of competitive interactions[504,636,673] (for example, increasing aggression between species[636]).

Overall, changes in habitat availability, sea temperature and nutrient cycling have increased competition across the Region. The increase in competition is likely to be having a negative effect on species and habitats, and the process is therefore considered to have deteriorated in condition since 2014.

3.4.10 Connectivity

Connectivity encompasses linkages between different habitats and the movement of species between landscapes and seascapes. It includes processes such as larval dispersal, migration, current flows, and those that connect coastal ecosystems to the Reef. For marine habitats, the main connectivity mechanism is water currents that link habitats and transport larvae. Due to their isolation, islands are highly reliant on wind, water and migratory birds to transport plant seeds.[674] Coastal ecosystems are also connected to the Region by the intertidal areas, river catchments, and groundwater, and they can influence the condition and resilience of the Reef (Section 3.5).[675]

Connectivity operates on a variety of spatial and temporal scales and is fundamental in determining a species' population dynamics and structure, genetic diversity, and resilience.[676,677] Patterns of connectivity among reefs within the Region play a critical role in supporting fisheries production. For example, fish populations in no-take marine reserves supply 83 per cent of coral trout larvae and 55 per cent of stripey snapper larvae to areas open to fishing in the Keppel Island group.[618]

Animal migration patterns are an important component of population and ecosystem connectivity. Migrations can range from small (between reefs) to long-range movements of hundreds or thousands of kilometres.[678] Whale migration is recognised as one of the superlative natural phenomena that contribute to the Reef's outstanding universal value. Several species of conservation concern (for example, humpback and dwarf minke whales), migrate through the Region from May to September for feeding and breeding, connecting the Region to feeding grounds in Antarctica. Nesting and foraging grounds of marine turtles connect the Region with the Arafura and Coral seas.[679,680] Seabirds and shorebirds also use the Region and adjacent Coral Sea as important stopover points to rest and feed as part of their larger migration.[371,373,375] For example, wedge-tailed shearwater birds travel between 300 and 1100 kilometres from their breeding colony at Heron Island to feed in the Coral Sea.[681] Emerging evidence indicates that coastal sharks migrate through coastal habitats and mid-shelf reefs of the Region.[682]

Connectivity within the Region is crucial for recovery from disturbance

Barriers to connectivity can reduce water quality and biodiversity.[43] Artificial barriers, such as dams, in the Catchment impede connections for fish and other aquatic fauna.[683] Many fish species use coastal wetlands as nurseries or breeding grounds, and habitat removal or alteration disrupts their life cycles.[684,685,686] The movements of juvenile blacktip reef sharks from sheltered coastal habitats to offshore coral reefs when they reach maturity highlight the importance of connectivity patterns to species conservation in the Region.[687]

Currents and wind can play major roles in connectivity, acting as transport highways for water, food and larvae (Section 3.2.1). Modelling has predicted that the recovery potential of seagrass meadows in the northern Region is greatly influenced by floating fragments, fruits and seeds from southern meadows, and that highly connected meadows, such as Cleveland Bay in Townsville, have higher resilience and assist the recovery of other meadows.[80,688] Modelling has also predicted a high level of connectivity of crown-of-thorns starfish across the Region, whereby some reefs could act as important sources and sinks for larval dispersal.[423] The dominant pattern of connectivity for coral larvae is from north to south[689], exemplified by the decline of coral recruitment in the northern and central regions in 2018.[96] Currents are influenced by a range of factors, and can shift in response to changing thermal patterns (Section 3.2.1). Slight shifts in currents could have significant effects on the Region's connectivity, increasing foraging distances for birds, changing dispersal of turtle hatchlings[38] and reducing or enhancing larval flow in some areas.[424]

Changes to connectivity patterns can drive a redistribution of species.[690] Evidence indicates this is already occurring with poleward transitions of reef fishes to subtropical areas.[691,692] Any changes to spatial and temporal connectivity patterns will have flow-on implications for species and the communities that rely on the Reef.[693,694] This could profoundly affect marine ecosystems by forging new connections that enable introduction of invasive species[691,695,696,697] and disease.[698]

Connectivity with some coastal ecosystems remains disrupted and the effects of climate change have radically altered connectivity patterns of corals. Overall, connectivity of species and habitats within the Region has deteriorated since 2014.

3.5 Current condition and trends in coastal ecosystems that support the Great Barrier Reef

Seven coastal ecosystems are graded. Heath and shrublands remain in very good condition and two coastal ecosystems (saltmarshes and rainforests) remain in good condition. Four coastal ecosystems continue to be in poor condition.

↔

Full assessment summary: see Section 3.7.4

Coastal ecosystems include those from the top of the Catchment (defined by the Great Dividing Range) to the marine inshore ecosystems within the Region, they are not restricted to waterways or the coastline. The coastal ecosystems referred to in this section are predominantly terrestrial and include: saltmarshes, freshwater wetlands, forested floodplains, heath and shrublands, grass and sedgelands, woodlands and forests, and rainforests (Section 2.1 Figure 2.1).[102,675]

The condition of the Reef benefits from connections with healthy and functioning ecosystems in the Catchment.[699] The functions coastal ecosystems provide to the Reef include physical processes (such as sediment and water distribution and cycling), biogeochemical processes (such as nutrient and chemical cycling), and biological processes (such as connectivity, habitat and food provisioning).[43,102] For a coastal ecosystem to function normally, the interactions between these natural ecological processes, the physical environment and its organisms must be reasonably intact and working efficiently.

Healthy, functioning coastal ecosystems are critical for the long-term health of the Reef

Coastal ecosystems also provide ecological services. In the context of this section, ecological services include benefits to the values of the Reef.[102] For example, intact coastal ecosystems can prevent major erosive processes (like gully erosion) and abundant ground cover may decrease sediment and nutrient loads entering the Region.[467] Connectivity is an essential function of coastal ecosystems (Section 3.4.10). The connectivity between coastal ecosystems and the Reef is provided by ecosystems dominated by both remnant and regrowth (non-remnant or previously cleared) vegetation, as well as modified coastal ecosystems. Connectivity plays an important role in providing suitable feeding and breeding areas for many marine species.[102] For example, it is known that at least 78 reef and estuarine fish species, including mangrove jack[700], use freshwater systems for part of their life cycle.[102]

In 2014, the assessment of condition of coastal ecosystems relied on an analysis of the importance of maintaining their function for the health and resilience of the World Heritage Area.[102] That analysis remains useful and informs this assessment, but has not been repeated. Since 2014, management tools (such as hydrological connectivity maps that inform catchment management approaches) have improved understanding of function.[462,701] However, management tools do not measure current condition (or function). Instead, the remaining spatial extent of each coastal ecosystem is the primary indicator of condition until such time as more broadscale current condition and function data are available.

Rainforest canopy, Green Island. © Dieter Tracey

The current vegetation extent data are compared to the vegetation extent before European settlement (Table 3.1). The coastal ecosystems have been grouped based on broad vegetation group classifications.[702] Broad vegetation groups are higher level groupings of vegetation communities and regional ecosystems that provide an overview of major ecological patterns and relationships across Queensland. Since 2014, these classifications have been updated, so some coastal ecosystems are grouped differently compared with 2014; for example, some dry eucalypt and open woodlands are now included in woodlands (rather than heath and shrublands). For this reason, the previously published pre-European settlement data and the 2009 data of remaining vegetation extents have been re-analysed (Table 3.1). The data in the table are distinguished from the woody vegetation clearing rates[703,704], which include vegetation that has previously been cleared (Box 3).

Table 3.1 Changes in the extent of coastal ecosystems in the Catchment before European settlement, 2009 and 2015
The 2014 Outlook Report outlined the remaining extent of terrestrial habitats (renamed to coastal ecosystems) since European settlement. The current extent and trend since 2009 of coastal ecosystems is presented (being remnant vegetation only; or more broadly, vegetation that has not previously been cleared). Source: Adapted from Neldner *et al.* 2017[702] and Kelley and Ryan 2018[705]

Coastal ecosystem (remnant)	Total area before European settlement (km²)	Total area remaining (km²)		Proportion remaining in Catchment (per cent)
		2009	2015	2015
Saltmarshes	2187	1870	1867	85
Freshwater wetlands	1668	1357	1357	81
Forested floodplains	50,060	29,116	29,037	58
Heath and shrublands	3178	2972	2970	93
Grass and sedgelands	11,897	5730	5721	48
Woodlands and forests	323,809	196,532	195,938	60
Woodlands	228,642	157,088	156,609	68
Forests	95,167	39,444	39,329	41
Rainforests	27,413	17,878	17,869	65

Forest stream in the upper Mulgrave River catchment. © GBRMPA 2014

BOX 3

Deforestation — woody vegetation loss

Vegetation clearing in the Catchment, specifically of woody vegetation, has increased since 2009 (Figure 3.12). Woody vegetation occurs across several coastal ecosystems (including some freshwater wetlands, forested floodplains, shrublands, woodlands, forests and rainforests). Woody vegetation includes both remnant and non-remnant vegetation[703], so its remaining extent cannot be assessed within just one of the coastal ecosystems discussed in this section.

The *Statewide Landcover and Tree Study*[703,704] is a vegetation monitoring program that reports annually on the woody vegetation loss in Queensland. The total area of woody vegetation cleared in the Catchment was at its lowest between 2008 and 2010, at approximately 250 square kilometres per year. The 2009 Outlook Report highlighted further clearing of coastal habitats as a high risk, which led to a new and separate assessment of terrestrial ecosystems in 2014. The 2014 Outlook Report elevated the risk posed by modifying coastal habitats to very high. Since that time, the clearing rate in the Catchment increased overall, peaking at 47 per cent (1660 square kilometres) of the total statewide woody vegetation clearing rates in 2016–17.[703,704] The increase in clearing of woody vegetation coincided with major changes to the Queensland vegetation clearing legislation in 2013.[706,707] These vegetation management laws were reinstated in mid-2018 to provide consistent protection to regrowth vegetation in all Reef catchments.[708]

Land clearing is a major contributor to climate change due to the loss of carbon storage habitats, as well as changes in rainfall and temperature dynamics.[701] Historically, intensive and sprawling anthropogenic land uses across the Catchment have shaped the extent of clearing; this has not altered (Section 6.4). In 2017–18, 93 per cent (approximately 3690 square kilometres) of the total statewide woody vegetation cleared was primarily for increased pasture for grazing. This represents a two per cent increase since 2014–15. Whereas, secondary purposes accounted for a very small proportion of the total clearing: forestry (six per cent), cropping (one per cent), and mining, infrastructure and settlement (less than two per cent in total).[704]

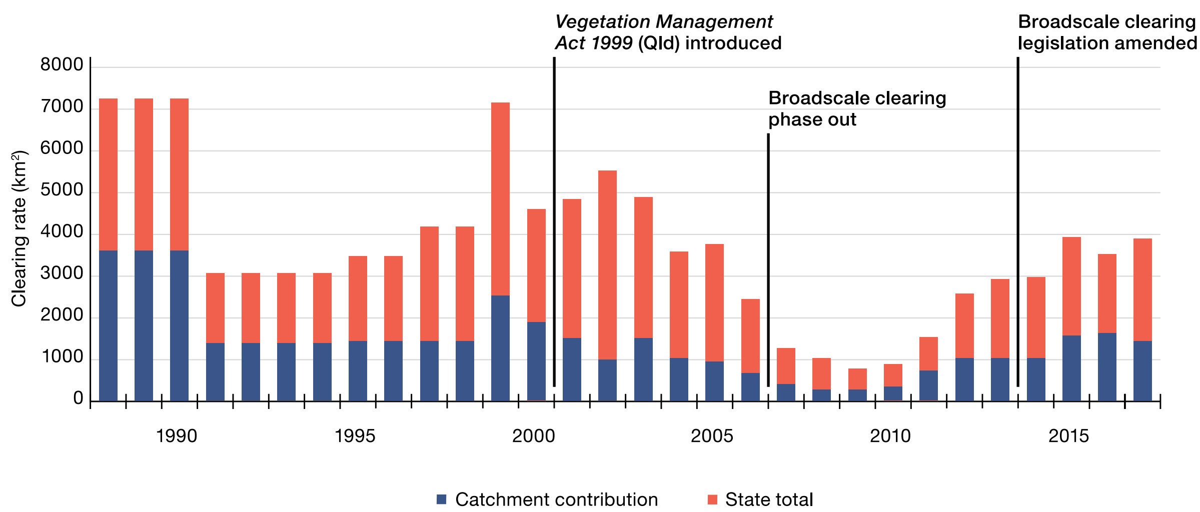

Figure 3.12 Woody vegetation clearing rates in the Catchment, 1988–2017
Values in this figure are an estimate of the clearing rate occurring in the 12-month period to 1 August.[703] Source: Adapted from Department of Science, Information Technology and Innovation (Qld) 2017[703] and Department of Environment and Science (Qld) 2018[704]

3.5.1 Saltmarshes

Saltmarshes are coastal ecosystems that occur in the upper intertidal area of estuaries and at the interface of marine and terrestrial environments.[709,710] This ecosystem provides intermittent feeding areas for many marine species, including various commercial fish and prawn species such as mullet and tiger prawns. Saltmarshes are vulnerable to anthropogenic pressures (such as direct use by vehicles[711], fishing and illegal dumping), as well as excess nutrient, sediment and pesticide loads.[43] Even so, little change in extent has occurred since 2014 (approximately 85 per cent of the pre-European settlement extent remains; Table 3.1).[705] A major threat to saltmarsh function is artificial barriers that prevent tidal influence into the ecosystem (Section 6.4). Given statewide regulatory controls have prohibited the construction of infrastructure like ponded pastures since the early 2000s, new infrastructure of this kind is no longer considered a widespread threat.[712,713] However, ongoing management of legacy infrastructure remains a risk to the ecosystem services saltmarshes provide to the Reef. In an attempt to remediate some of the impact from existing infrastructure, projects have been undertaken on a limited scale since 2014 to re-establish connection through culverts.[714]

Saltmarshes are essential for ecological function, however, their condition is not well known

Regulations protecting against unlawful destruction, removal or damage influence the extent of all marine plants (many of which are found in saltmarshes). The interaction between mangroves and saltmarshes also influences the extent of saltmarshes. It is evident that the movement of mangroves into pockets of saltmarsh ecosystems may result from sea-level rise and climate-driven environmental change.[711] While the estimated extent of saltmarshes is monitored remotely, condition data are limited to localised detailed surveys completed on an *ad hoc* basis.[715]

3.5.2 Freshwater wetlands

While freshwater wetlands can include rivers, for the purpose of this report, this coastal ecosystem only includes lacustrine (lake) and palustrine (vegetated swamp) wetlands located on coastal lowlands and floodplains characterised by seasonal inundation.[705,716] This coastal ecosystem is included in the extent of woody vegetation (Box 3). Freshwater wetlands provide essential functions and services in, and to, coastal and marine ecosystems. For example they provide nurseries for freshwater and marine species[43] and are used by barramundi moving between estuarine and freshwater habitats at different life stages.[717] However, cumulative pressures on this ecosystem's ability to function efficiently continue to come from poor water quality and changes in hydrology.[43] Human-induced pressures include: expanding urban land uses and transport infrastructure (roads); the introduction and spread of aquatic and terrestrial invasive species;[43] and, for some sites, unrestricted access of livestock.[43,718] A changing climate is a significant threat to wetlands, potentially altering wetting and drying cycles, increasing fire frequency and intensity, and raising sea levels.[719]

Connectivity between wetlands and the Reef is essential to the health of the Region

The importance of freshwater wetlands is reflected in new Queensland Government catchment targets requiring no net loss of wetland extent[527], and a net improvement in the condition of natural wetlands and riparian vegetation that contribute to the Reef's resilience and ecosystem health.[9] Since 2009, no additional clearing of freshwater wetlands has been recorded; 81 per cent of the pre-European extent is estimated to remain in the Catchment (Table 3.1).[705] Managers reported on wetland condition for the first time in 2016.[43] Measured against the *Reef Water Quality Protection Plan* 2013[720] target, floodplain wetlands overall are in moderate condition and under moderate exposure to pressures.[721]

3.5.3 Forested floodplains

Forested floodplains are open forests and woodlands on drainage lines or low-lying areas that intermittently flood.[702] This coastal ecosystem is included in the extent of woody vegetation (Section 3.5 Box 3). Forested floodplains benefit the marine ecosystem by providing physical processes that slow, capture and transform or retain nutrients and sediments before they enter the Region. The main threats to forested floodplains continue to be anthropogenic impacts and climate change. Limited contemporary studies have considered the condition of forested floodplains.[102] The current extent of this ecosystem is approximately 58 per cent of the extent before European settlement (Table 3.1).[705]

3.5.4 Heath and shrublands

Heath and shrublands often occurs in coastal locations, including dunefields, sandplains and headlands.[702] This ecosystem helps slow the overland flow of water, prevents erosion, transforms nutrients and sediments, and is important as a buffer on steep coastal hill slopes.[102] About 42 per cent of this coastal ecosystem is located in protected areas,[705] which may have resulted in the ecosystem being reasonably intact (93 per cent of the extent before European settlement remains; Table 3.1). The Cape York NRM region is estimated to have retained all of its remnant heath and shrubland areas.[705] This ecosystem is vulnerable to anthropogenic impacts (clearing and grazing) and climate change, specifically sea-level rise. Condition data are lacking for heath and shrublands.

Overall, the extent of heath and shrublands is stable, although highly sensitive to human disturbances

3.5.5 Grass and sedgelands

Grass and sedgelands is typically composed of perennial native grasses (such as Mitchell, tussock and bluegrass) with limited trees.[702] This coastal ecosystem often occurs in temporarily waterlogged areas within minor basins or small depressions, and can be associated with wetlands. More than half of the grass and sedgelands in the Catchment has been cleared since European settlement; the Mackay–Whitsunday region has had the greatest loss (approximately 14 per cent remaining of the extent before European settlement). Since 2014, no further loss of this ecosystem has been recorded (Table 3.1).[705] The grass and sedgeland ecosystem continues to be susceptible to anthropogenic impacts, specifically altered hydrological processes. Data on the condition data of this coastal ecosystem remains a knowledge gap.

More than half of the grass and sedgelands has been cleared since European settlement, but the current extent remains stable

Vegetation and ground cover are the primary controls of gully erosion, providing protection against scouring and reducing overland flow velocity. Image: Springvale Station, Cape York. © Department of Environment and Science (Qld) 2017

3.5.6 Woodlands and forests

Woodlands and forests in the Catchment are located on flat to gently undulating coastal lowlands and alluvial plains, characterised by a number of eucalypt species making up the canopy. The woodland and forest ecosystem affects the Reef's physical processes through its contribution to regulating sediment supply. Furthermore, it reduces the velocity of floodwaters by slowing overland flow, moderating erosion that may lead to gully erosion and sediment loss.[102] Monitoring the area of this ecosystem is well established; it makes up the greatest extent of the woody vegetation monitoring study (Section 3.5 Box 3). Forests are generally stable in extent, whereas steeper reductions have been observed in the extent of woodlands (Table 3.1). The Cape York and the Wet Tropics regions have the greatest extent of remaining remnant woodlands and forests ecosystem (88–99 per cent of the extent before European settlement), whereas the Fitzroy and Burnett–Mary regions have dropped to approximately 30–37 per cent of the extent before European settlement.[705] No new data on the condition of this coastal ecosystem have been released since 2014.

The extent of woodlands and forests is greatly reduced compared to that before European settlement, however, reductions since 2009 have been limited

3.5.7 Rainforests

Rainforests include vine forests of the Wet Tropics and Cape York regions and stretch south to the evergreen vine forests in the Burnett–Mary NRM region. Rainforests are located in high-rainfall highland areas, and occasionally on lowlands, beach ridges and islands.[702] Rainforests are included in the extent of woody vegetation (Section 3.5 Box 3).

The Cape York and Mackay–Whitsunday regions retain nearly all the rainforest ecosystem they had before European settlement

Monitoring the extent of this ecosystem is well established and published annually.[703,704] Rainforests in the Burnett–Mary and Fitzroy NRM regions have experienced the greatest clearing rates since European settlement; their remaining extents being 30 and 35 per cent, respectively. Conversely, the Cape York and Mackay–Whitsunday NRM regions retain near full extent of their pre-European settlement rainforest ecosystems (99 and 91 per cent, respectively).[705] However, in late 2018 the Mackay hinterland was devastated by bushfires. At the time of writing, no published data are available on the impacts of the fires. Overall, it is estimated that 62 per cent of the Catchment's rainforests are located in protected areas. Limited areas of remnant rainforest have been allocated to protected areas since 2014. The main threats to this coastal ecosystem continues to be climate change (specifically the increase in frequency and intensity of extreme temperatures and fires), feral animals and ongoing fragmentation as a result of anthropogenic pressures.[722] The broad condition of rainforests is a knowledge gap.

3.6 Current condition and trends of outbreaks of disease, introduced species and pest species

Four components are graded. Outbreaks of disease, introduced species and other outbreaks remain in good condition. However, outbreaks of crown-of-thorns starfish continues to be graded as very poor.

↔

Full assessment summary: see Section 3.7.5

3.6.1 Outbreaks of disease

Diseases are infections of plants and animals by pathogenic microorganisms, such as bacteria, viruses, fungi and parasites. Although many of these microorganisms are naturally present in the environment and usually do not cause widespread disease, outbreaks can occur when microorganism abundance increases rapidly or the immunity of a potential host is compromised.[578,723] Factors such as climate change, a general decline in habitat condition and increased population density, increase disease prevalence and virulence, and rates of disease transmission.[724,725,726]

Disease can have a significant negative effect on population structure, causing rapid population declines or, in extreme cases, hastening species extinctions.[578] Disease affects both host organisms and associated species. It can have flow-on effects to ecosystem function, particularly if the disease impairs or kills habitat-forming species, such as corals.[727,728,729] Not all diseases are lethal; sublethal effects of disease include reduced rates of reproduction and growth.[212]

Diseases are known to have affected a number of marine organisms, such as turtles, dolphins, urchins, sponges, molluscs, seagrasses, fishes and crabs.[730,731,732] For example, disease prevalence was 25 per cent higher for fishes and mud crabs assessed in and around Gladstone harbour in 2012 than those from control sites[733]. Since 2018, mud crab lesions have dropped to less than three per cent.

Figure 3.13 Coral trout exhibiting symptoms of disease
Coral trout exhibiting symptoms of disease (fin rot, red eruptive sores, small cysts on pectoral fins) were caught in the vicinity of severely and moderately bleached reefs offshore northern Queensland in June, 2016. © Department of Agriculture and Fisheries (Qld) 2016

In the Region, at least eight different diseases have been recorded from 40 different coral species.[217,734] Surveys undertaken between 2014 and 2018 recorded disease on several reefs across the entire Region.[735] The incidence of coral disease increased sharply in the winter of 2016 following mass bleaching and continued into the summer of 2017. Incidence of coral disease was greatest on reefs that had experienced the longest exposure to warmer than average sea surface temperatures in the winter of 2016 and summer of 2017.[96,736] Although it is unknown what proportion of corals in the Region were affected, one study observed a reduction in coral cover by more than half due to a combination of bleaching and white syndromes disease in early 2017.[736]

With increasing global warming and poor water quality, disease prevalence may also increase in fish species.[725] For example, in April 2016, disease was detected in coral trout caught near reefs in the northern Reef that had been exposed to record-breaking sea surface temperatures during the summer. Although the disease was never identified, symptoms included fin rot, red eruptive sores, small cysts on pectoral fins and widespread sandpaper bumps on the body of the fish (Figure 3.13). Given the prolonged exposure to high sea surface temperatures in 2016, it is likely these fish succumbed to physiological stress. It is unclear what longer-term ecological implications will manifest in coral trout and other fish species across the northern two thirds of the Reef following the 2016 and 2017 mass bleaching events.

Incidence of disease in the Region will increase with temperature increases associated with global warming, potentially resulting in disease hotspots.[737,738,739,740] Injuries to corals from coral predators[741,742,743] and damselfish[744], increased sediment and turbidity[745] and abrasion from marine debris[580] also influence disease transmission in coral. *Drupella*, a coral-feeding snail, can transmit brown band coral disease between colonies.[742] These small predatory snails can aggregate in large numbers (Section 3.6.4)[746,747], and so they are a significant disease vector.[742] New diseases arriving in the Region as a result of changes in ocean currents (and consequent connectivity patterns) due to climate change are an emerging risk.[698]

Marine turtles have been found with blood flukes, septicaemia and fibropapilloma infections[337], but only in small numbers, and these diseases do not appear to have increased since 2014. Overall, outbreaks of disease have been fairly stable since 2014, with higher incidences after thermal extremes in 2016 and 2017.

3.6.2 Outbreaks of crown-of-thorns starfish

Outbreaks of crown-of-thorns starfish are ongoing and causing coral decline

Crown-of-thorns starfish (previously referred to as *Acanthaster planci*, reclassified as *Acanthaster* cf. *solaris*[748]) are native coral predators on the Reef. At natural densities (less than one starfish per hectare)[749], the starfish do not pose a threat to coral reefs because coral growth rates exceed predation rates. However, when densities of starfish reach a point where the consumption of coral tissue exceeds coral growth (approximately 15 starfish per hectare)[750], an outbreak is established.[751] Since the early 1960s, the Region has experienced four destructive outbreaks. This frequency is unsustainable, particularly given other cumulative and broadscale pressures affecting the Region.

An outbreak spreads along the Region primarily when adults spawn (in the warmer months from December to February) and their larvae are transported by currents to other reefs, some tens to hundreds of kilometres away.[752] Once larvae settle on the reef, they feed initially on crustose coralline algae[753] before transitioning to a diet of coral tissue (Figure 3.14).

Figure 3.14 Juvenile and adult crown-of-thorns starfish
Left: Juvenile starfish feeding on crustose coralline algae before switching to a coral diet. © Jennifer Wilmes.
Right: Lethal injection of adult starfish feeding on a large plate coral. © GBRMPA, photographer: Daniel Schultz

In 2010, the Reef experienced the initial stages of its fourth crown-of-thorns starfish outbreak since the 1960s.[752] These outbreaks have followed a common pattern, initiating approximately every 15 to 17 years in the region between Lizard Island and Cairns on reefs offshore from the Wet Tropics river catchment.[424,752] These primary outbreaks subsequently spread out from the initiation zone in waves, mainly through the transport of crown-of-thorns starfish larvae on ocean currents. These waves of secondary outbreaks spread southward at a rate of approximately 60 kilometres per year and can persist for more than 10 years.[754] The primary outbreaks that initiate in the region between Lizard Island and Cairns may also spread north, however, the dynamics of a northern spread are not well understood.

Between 2014 and 2018, the outbreak that started in 2010 in the Cairns–Cooktown Management Area, gradually spread south, to reefs off Innisfail and Townsville.[735] In 2017, an independent outbreak was identified in the Swain Reefs.[735] In 2018–19, surveys of 57 reefs in the Far Northern Management Area found no signs of outbreaks, while surveys in the Mackay–Capricorn Management Area found outbreaks on 16 per cent of the 75 reefs surveyed.[735]

Outbreaks of coral-feeding crown-of-thorns starfish, coupled with impacts from coral bleaching, have caused extensive coral decline across the Region.[755] In the absence of other disturbances, the recovery of coral reefs following starfish outbreaks takes at least 10 years, with coral reefs protected in no-take areas recovering more quickly than those where fishing is allowed.[756] However, windows of opportunity for recovery following outbreaks are decreasing, given other cumulative stressors affecting coral reefs.

Attempts to manage crown-of-thorns starfish outbreaks includes mitigating several factors that contribute to outbreaks and their prevalence (including poor water quality and removal of predators through fishing), and direct control through culling[751] (Section 7.3.12 Box 13). Controlling outbreaks at a local scale is considered one of the most feasible management actions to reduce rates of coral mortality after an outbreak has established and to enable the ecosystem to cope with other pressures.[757,758] As well as direct loss of coral tissue from crown-of-thorns starfish predation, the potential flow-on effects (such as loss of diversity, damage to reef structure and algal overgrowth) also degrade the overall resilience of the ecosystem[759] (Chapter 8).

The underlying causes of outbreaks are multifaceted with no single trigger categorically proven to initiate outbreaks.[757,758] Nutrients in the water column from natural upwelling and land-based run-off, hydrodynamic conditions, coral availability and low abundance of predators of crown-of-thorns starfish may all combine to provide positive outbreak conditions on the Reef.[424,760,761,762] For some time, the giant triton snail was considered one of the few predators of crown-of-thorns starfish.[763] However, it is increasingly clear that many coral reef organisms, including other invertebrates and fish (for example, small damselfish and emperors), prey on crown-of-thorns starfish at some stage in their life cycle.[764] Some of these predators (such as emperors) are fisheries targets. Healthy predator populations are likely to be important in the top-down control of starfish populations and prevention of future outbreaks.[754,762]

As at 2019, outbreaks are most severe in the central and southern areas of the Reef. Overall the trend remains stable.

3.6.3 Introduced species

Introduced species or 'pests' include non-native plants or animals that establish beyond their natural range and threaten values within their new range. Pests can be spread by both natural vectors (wind, currents and birds)[765,766] and human-related vectors (on camping equipment, the hull of a ship, or materials moved to and between islands). Introduced species are a threat to native plants and animals because they compete for food and space, and in some cases may directly prey on native species (for example, feral pigs prey on marine turtle eggs).

Since 2014, several pests have been eradicated from islands

Australian waters house approximately 200 introduced marine species.[767] The majority have been transported within the marine environment by ships (for example, the Asian green mussel) or have entered Australian waters from legacy aquaculture outflows. Since 2009, seven exotic marine pest detections have occurred within Queensland ports, four of which were in the Region (Gladstone 2009, Cairns 2012 and 2014, and Hay Point 2013). The last recorded incursion within the Region was in December 2014, when two Asian green mussels were found on a navy ship in Cairns.

Coordinated marine pest monitoring is not undertaken at smaller marinas and ports used by recreational and commercial vessels travelling from international waters through the Reef. However, Biosecurity Queensland is currently working on a *Marine Pest Prevention and Preparedness Project* to increase maritime stakeholder knowledge and awareness of how to minimise the threat of marine pests through surveillance, reporting and recommended boat hygiene practices. Biosecurity Queensland is also developing a pilot port surveillance program, working with the five major Queensland ports to build capability in marine pest surveillance and monitoring.

Established terrestrial pests are more likely to persist on islands and cays that are disturbed or have been modified in some way.[765] With an increasing coastal population and greater promotion of island-based tourism in areas where the Reef is recovering from disturbances (for example, the Whitsunday islands), there may be an increased risk of

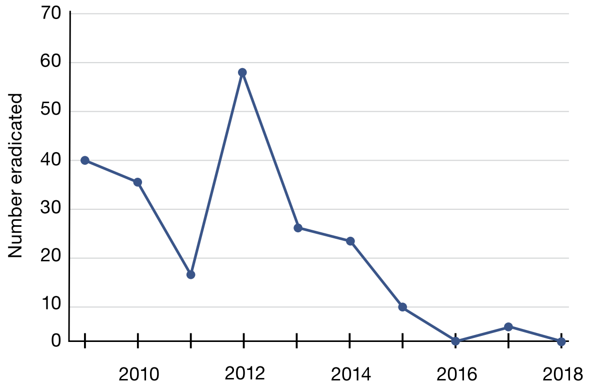

Figure 3.15 Number of goats removed from High Peak Island, 2009 to 2018
An ongoing targeted program began in 2009 and resulted in full eradication in 2018. Source: Queensland Parks and Wildlife Service

human transmission of pests to islands and cays. Since 2014, an improved approach to island biosecurity has been implemented through prescriptive quarantine and surveillance measures. The Queensland Government 'Be Pest Free' community awareness and education program educates island visitors on how to avoid the inadvertent introduction of pest plants and animals. Islands that receive regular barge services (such as Magnetic Island, Green Island and some Whitsunday islands) and campers have a higher risk of receiving new pest introductions than more isolated, less visited islands.

Since the 1970s, there has been a gradual trend of increasing eradication successes on islands and cays around the Whitsundays and Capricorn Bunker group (Box 4). Since the 2014 Outlook Report, several introduced species have been eradicated from islands where they were previously recorded (for example, goats have been eradicated from High Peak and St Bees islands (Figure 3.15), and rats from Frankland and Barnard islands). Pest management is ongoing on other islands, mainland beaches and coastlines.

The occurance of introduced species has remained stable across the Region. Effective eradication has occurred in some areas and limited infestations have been recorded in, and adjacent to, the Region.

BOX 4

Pest eradication restores *Pisonia* forest and seabird breeding site

The scale insect (*Pulvinaria urbicola*) in outbreak numbers can be a pest, attaching to plants and extracting sap, weakening and eventually killing the plant. Certain species of ladybird and parasitic wasp are natural predators of the scale insect; however, if their numbers are low it is hard to control without intervention. On two islands off Yeppoon (Tryon and Wilson islands), infestations of the scale insect grew to devastating levels when aided by the introduced African big-headed ant. The ant protects the scale insect from natural predators and feeds on a honey dew excretion produced by the scale insect. As well as undermining natural predation, the ant moves scale insects between plants, spreading the infestation.

Pisonia forests provide critical seabird nesting habitat, stabilise sediments and suppress other plants through shading.[27] From 1993 to 2003, the scale insect infestation had severe ecological impacts at Tryon Island, decimating the island's *Pisonia* forests. This led to a change in the composition of the island's vegetation and seabird communities. Wedge-tailed shearwaters continued to breed, however, thick grasses and weeds hindered ground movement of birds and their take-off runways. Transient species, such as the tawny grassbird were recorded more regularly after the vegetation had shifted from forest to more open habitat.

Top: Decimated area of Pisonia grandis forest on Tryon Island. © Queensland Parks and Wildlife Service 2006, photographer: Joy Brushe
Bottom: The same location in 2016. © Queensland Parks and Wildlife Service 2016, photographer: Joy Brushe

Pest ants were baited from 2006, and in 2016 eradication of the island's African big-headed ants was confirmed. The intervention program also focussed on restoring the island's original forest. More than 3000 *Pisonia* cuttings were planted and the forest has started to recover its closed canopy, supressing weeds. This vegetation renewal has also re-established nesting habitat for black noddies and wedge-tailed shearwaters, with numbers of both increasing.

The lessons learned at Tryon Island provided the basis for the highly successful outbreak response at Wilson Island in 2006 and 2007. Knowledge was gained on how to bait and kill the introduced ants, bolster natural predator numbers and effectively restore *Pisonia* forest ecosystems.[768] Managers now have the science and intervention knowledge to successfully prevent, treat and protect *Pisonia* forests from the scale insect pest throughout the Reef.

3.6.4 Other outbreaks

Other outbreaks includes native species (as opposed to introduced species; Section 3.6.3) that experience a rapid increase in abundance, biomass or population. Outbreaks of the naturally occurring crown-of-thorns starfish and coral disease were examined previously (Sections 3.6.1 and 3.6.2). Outbreaks and blooms are often a sign of ecosystem stress and can be harmful or lethal to other marine species. Some outbreaks can also pose a threat to human health, either through direct consumption of ciguatoxins in fish, inhalation of microscopic organisms causing the outbreak[769], or exposure to toxic cyanobacteria in water.

Trichodesmium is a pelagic blue-green alga that can create slicks when significant numbers of the cells join together and float to the water surface. When these slicks are exposed to light the algae die, leaving floating pungent slicks that look like sawdust on the surface of the water and are commonly mistaken for oil spills (Figure 3.16). Slicks are more common under hot, calm, doldrum conditions in spring and summer, and accumulation is aided by slow, circulating surface currents.[770] *Trichodesmium* plays an important role in nitrogen fixation, and produces a large amount of the nitrogen available to the Reef system.[771,772]

Figure 3.16 *Trichodesmium* slick around Hinchinbrook Island
© GBRMPA 2019

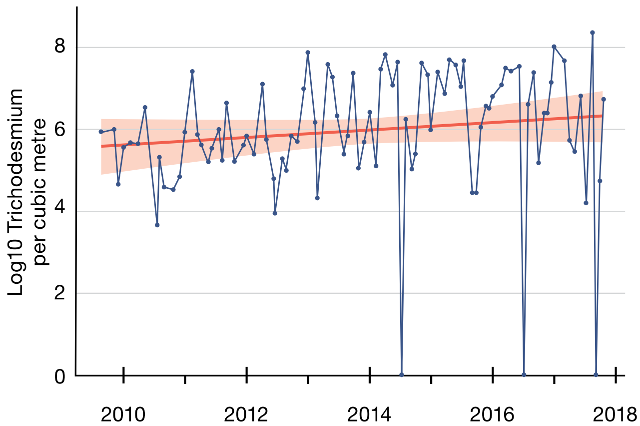

Figure 3.17 Abundance of *Trichodesmium*, Yongala IMOS National Reference Station, 2009–2017
Source: IMOS National Reference Station 2010-2018[773]

When the blooms outbreak into large slicks, they can become toxic, particularly in shallow, still waters, affecting other marine life (predominantly fish) and posing a risk to human health. While limited broadscale monitoring of *Trichodesmium* occurs across the Region, long-term data have been recorded near the Yongala Wreck (offshore from Ayr) since 2010, indicating a long-term gradual increase in the abundance of *Trichodesmium*[773] (Figure 3.17). Seasonal fluctuations in abundance occur, with lower abundances associated with winter periods.[773]

Drupella are coral-eating marine snails that occur naturally on the Reef. When *Drupella* snails increase to outbreak numbers they can significantly damage corals through direct predation and spreading disease.[742] There is no evidence to suggest that *Drupella* snails undergo regular, large-scale outbreaks like crown-of-thorns starfish. The triggers for *Drupella* snail outbreaks are also not well understood. However, overfishing of predators (such as triggerfish and wrasses)[774], elevated nutrients and global warming may exacerbate outbreaks.[775] Recent evidence from the Maldives identified a significant increase in *Drupella* snails following a coral bleaching event in 2016, with snails targeting colonies that had resisted the bleaching.[776] On the Reef, some tourism operators have reported high densities of *Drupella* snails at several tourism sites off Cairns.[777] However, due to lack of data it is unclear whether *Drupella* outbreaks have increased across the Region following the 2016–2017 coral bleaching events.

Outbreaks and blooms can be triggered by changed environmental conditions. For example, blooms of irukandji jellyfish in the Region during summer months coincide with the easing of prevailing south-easterly trade winds.[778] Elsewhere in the Pacific, toxic algal blooms associated with record-breaking high sea surface temperatures in 2016 have occurred. For example, a region in Chile declared a state of emergency when a widespread toxic algal outbreak caused mass mortality of fishes, shellfish, and birds, and hundreds of whale strandings.[779] This resulted in significant economic losses, with impacts on both human health and recreational use.

Outbreaks of some species are increasing in some areas, while *Drupella* abundance appears similar to levels seen before 2014, resulting in no consistent trend.

3.7 Assessment summary — Ecosystem health

Paragraph 54(3)(a) of the *Great Barrier Reef Marine Park Act 1975 requires '… an assessment of the current health of the ecosystem within the Great Barrier Reef Region and of the ecosystem outside that region to the extent that it affects that region'.*

This assessment is based on five assessment criteria:

- physical processes
- chemical processes
- ecological processes
- coastal ecosystems that support the Great Barrier Reef
- outbreaks of disease, introduced species and pest species.

3.7.1 Physical processes

Grading statements — physical, chemical and ecological processes

Very good
There are no significant changes in processes as a result of human activities.

Good
There are some significant changes in processes as a result of human activities in some areas, but these are not to the extent that they are significantly affecting ecosystem functions.

Poor
There are substantial changes in processes as a result of human activities, and these are significantly affecting ecosystem functions in some areas.

Very poor
There are substantial changes in processes across a wide area as a result of human activities, and ecosystem functions are seriously affected in much of the area.

Borderline
Indicates where a component or criterion is considered close to satisfying the adjacent grading statement.

Trend since last report

- ↑ Improved
- ↔ Stable
- ↓ Deteriorated
- – No consistent trend

Confidence

- ● Adequate high-quality evidence and high level of consensus
- ◐ Limited evidence or limited consensus
- ○ Inferred, very limited evidence

Grade and trend			Confidence		Criterion and component summaries
2009	2014	2019	Grade	Trend	
Good	Good ↓	Good ↓			**Physical processes:** The majority of physical processes have remained stable or continued to decline, except currents and cyclones and wind. Further changes to these processes are expected due to the continued influence of climate change and land-based run-off, with broad implications for the Region.
Very good	Very good ↓	Very good –	○	○	**Currents:** Ocean currents continue to transport and connect species and habitats.
Good	Good ↓	Good –	●	●	**Cyclones and wind:** Since 2014, over 60 per cent of the reef area within the Region has been exposed to destructive waves from five severe tropical cyclones. Location and intensity of cyclones remain highly variable. Given other cumulative impacts, cyclones have damaged the Region's structure and impacted its function, particularly around Lizard Island and the Whitsundays.
Good	Good ↓	Good ↔	●	●	**Freshwater inflow:** Between 2013 and 2018, freshwater flow was near or below the long-term average for the Catchment.
Poor	Poor ↓	Poor ↔	●	●	**Sediment exposure:** Sediment loads continue to contribute to the poor state of many inshore coastal and marine ecosystems. The majority of sediment is delivered to the Region during flood events and the amount varies between catchments.
Good	Good ↓	Good ↓	●	●	**Sea level:** Sea level is rising, with the fastest rates being recorded in the Region's north. Coastal areas, islands and cays will be most affected by increases in sea level.
Poor	Poor ↓	Very poor ↓	●	●	**Sea temperature:** Extreme thermal stress due to global warming occurred in the summers of 2016 and 2017, resulting in widespread coral mortality. Impacts on other organisms (such as fish and seabirds) are emerging.
Good	Good ↓	Good ↓	◐	◐	**Light:** It is likely that underwater light availability has decreased substantially in the inshore areas of the southern two thirds of the Region due to land-based run-off, resuspension of existing sediment in the system and extreme weather.

3.7.2 Chemical processes

Grade and trend			Confidence		Criterion and component summaries
2009	2014	2019	Grade	Trend	
	↓	↔			**Chemical processes:** The chemical processes within the Reef are generally in good condition. However, nutrient cycling continues to be affected by land-based run-off. Ocean salinity has remained stable largely as a result of low rainfall. Ocean pH has decreased as a result of climate change.
	↓	↔	●	●	**Nutrient cycling:** Since 2012, the dissolved inorganic nitrogen discharged to the Catchment has been generally lower than previous years, primarily due to low river flow.
	↓	↓	●	●	**Ocean pH:** Inshore areas are more vulnerable to ocean acidification than the open ocean due to higher respiration and nutrient levels. Ocean pH is slowly decreasing.
	↓	↔	●	◐	**Ocean salinity:** Localised changes to salinity occur as a result of freshwater inflow, largely affecting inshore areas. Overall, this process is stable.

3.7.3 Ecological processes

Grade and trend			Confidence		Criterion and component summaries
2009	2014	2019	Grade	Trend	
	↓	↓			**Ecological processes:** The majority of ecological processes on the Reef have deteriorated. Significant declines in the majority of coral cover throughout the Region are likely to have affected some key ecological processes, such as connectivity, symbiosis, reef building, competition and recruitment. However, as time lag effects are common after mass bleaching events, impacts may still be unfolding. Ecological processes are expected to continue to decline due to climate change impacts and inshore land-based run-off.
	↔	–	○	○	**Microbial processes:** Microbial processes are central to the flow of carbon through the ecosystem and are sensitive to changes in environmental conditions. Environmental stressors associated with a warming climate have disrupted microbial processes in corals and other organisms, lowering their ability to resist bleaching and disease. Very little information exists on microbial processes across the Region.
	↓	↓	◐	◐	**Particle feeding:** Particle feeding is undertaken by a broad range of species, including echinoderms, molluscs, sponges and corals. High nutrient levels have affected some particle feeders. Following two thermal stress events, there have been significant declines in particle-feeding corals in some areas. It is also likely that particle-feeding fish, which rely heavily on coral habitats for shelter, have also decreased.
	–	–	◐	◐	**Primary production:** Some seafloor primary producers, such as seagrasses and benthic algae, have increased in some areas. However, high levels of nutrients, sediment and temperature are causing negative impacts. Corals have declined sharply. Phytoplankton is variable across the Region and depends on a combination of freshwater inflow and nutrients.
	↓	↔	◐	◐	**Herbivory:** The process of herbivory supports nutrient cycling, is important for reinforcing a coral-dominated state through the removal of competing algae, and increases the productivity of seagrass meadows. Fish herbivore abundance has generally remained stable across the Region, with some changes in offshore locations. In high-sediment areas, and where macroalgae are dense, herbivory is reduced. The condition of herbivory as a process across the Region and the mechanisms that affect it are not well understood.
	–	–	◐	◐	**Predation:** Generally, changes in the abundance of reef-associated predators across the Region have been variable. A large group of predators, the sharks and rays, has been assessed as being in poor condition.
	↓	↓	◐	●	**Symbiosis:** Based on the unprecedented decline of coral cover and the changes in coral community composition, the majority of symbioses involving coral have been significantly affected since 2016. Many symbiotic relationships between small benthic invertebrates remain data deficient.
		↓	◐	◐	**Recruitment:** Recruitment is reduced for many key species, in particular, corals, fishes and some marine turtles and seabirds, largely due to chronic and acute disturbances.
	↓	↓	◐	◐	**Reef building:** Reef building has deteriorated, largely due to the combined effects of unprecedented declines in coral cover and crustose coralline algae in some areas in response to thermal bleaching events. The slow decrease in ocean pH affects reef building.

Grade and trend			Confidence		Criterion and component summaries
2009	2014	2019	Grade	Trend	
Good	Good ↔	Good ↓	○	○	**Competition:** Habitat loss and population declines are changing competition on a broad scale, which is likely to have flow-on effects on the fitness of organisms. It is likely that coral–algal competition has increased.
Good	Good ↓	Good ↓	◐	◐	**Connectivity:** Marine species and habitats remain connected. However, effects of climate change have altered connectivity patterns. Connectivity with some coastal ecosystems remains disrupted.

3.7.4 Coastal ecosystems that support the Great Barrier Reef

Grading statements — coastal ecosystems that support the Great Barrier Reef

Very good
All major habitats are essentially structurally and functionally intact and able to support all dependent species.

Good
There is some habitat loss, degradation or alteration in some small areas, leading to minimal degradation but no persistent, substantial effects on populations of dependent species.

Poor
Habitat loss, degradation or alteration has occurred in a number of areas leading to persistent substantial effects on populations of some dependent species.

Very poor
There is widespread habitat loss, degradation or alteration leading to persistent, substantial effects on many populations of dependent species.

Borderline
Indicates where a component or criterion is considered close to satisfying the adjacent grading statement.

Trend since last report

- ↑ Improved
- ↔ Stable
- ↓ Deteriorated
- ▬ No consistent trend

Confidence

- ● Adequate high-quality evidence and high level of consensus
- ◐ Limited evidence or limited consensus
- ○ Inferred, very limited evidence

Grade and trend			Confidence		Criterion and component summaries
2009	2014	2019	Grade	Trend	
	Poor	Poor ↔			**Coastal ecosystems that support the Great Barrier Reef:** A broad understanding of the condition of each coastal ecosystem remains a significant knowledge gap, even though some are subject to extensive management effort (saltmarshes, wetlands, woodlands and forests). Many grades and trends are limited or inferred. Since 2014, the woody vegetation clearing rate in the Catchment continued to increase. The main purpose for this clearing was for agriculture.
	Good	Good ↔	◐	◐	**Saltmarshes:** Historically, a small area of this ecosystem has been modified in the Catchment. More evidence is emerging about saltmarshes, yet little is known about the condition of this ecosystem.
	Poor	Poor ↔	◐	◐	**Freshwater wetlands:** No significant loss of extent and no significant new threats have occurred, but the impacts of climate change are unclear.
	Poor	Poor ↔	◐	○	**Forested floodplains:** Given the limited remaining extent and limited condition data available about the performance of this ecosystem for services and function to the Reef, the grade and trend are uncertain. There is insufficient new evidence to substantiate a change in grade or trend.
	Very good	Very good ↔	◐	◐	**Heath and shrublands:** Given the extent of heath and shrublands remains stable at nearly the full extent of the ecosystem pre-European clearing, the ecosystem is considered to be very good. However, little is known about the condition of this ecosystem.
	Poor	Poor ↔	◐	○	**Grass and sedgelands:** Grass and sedgeland extent remains stable, but overall this ecosystem has seen the greatest loss of all coastal ecosystems since European settlement. Limited condition data are available.
	Poor	Poor ↓	●	◐	**Woodlands and forests:** The extent of this ecosystem is stable, but continues to reduce from the nominal extent that remains from clearing after European settlement. Annual data are produced on the extent of woody vegetation clearing rates, and are the most robust data available.
	Good	Good ↔	◐	◐	**Rainforests:** Extent in the catchment remains stable. Although little is known about the condition of this ecosystem, the inferred protection of rainforests in protected areas increases the confidence in this grade.

3.7.5 Outbreaks of disease, introduced species and pest species

Grading statements — outbreaks				
Very good No records of diseases above expected natural levels; no introduced species recorded; no outbreaks; pest populations within naturally expected levels.	**Good** Disease occasionally above expected natural levels but recovery prompt; any occurrences of introduced species successfully addressed; pests sometimes present above natural levels with limited effects on ecosystem function.	**Poor** Unnaturally high levels of disease regularly recorded in some areas; occurrences of introduced species require significant intervention; pest outbreaks in some areas affect ecosystem function more than expected under natural conditions.	**Very poor** Unnaturally high levels of disease often recorded in many areas; uncontrollable outbreaks of introduced pests; opportunistic pests seriously affecting ecosystem function in many areas.	**Borderline** Indicates where a component or criterion is considered close to satisfying the adjacent grading statement.

Trend since last report

- ↑ Improved
- ↔ Stable
- ↓ Deteriorated
- − No consistent trend

Confidence

- ● Adequate high-quality evidence and high level of consensus
- ◐ Limited evidence or limited consensus
- ○ Inferred, very limited evidence

Grade and trend			Confidence		Criterion and component summaries
2009	2014	2019	Grade	Trend	
Poor	Poor ↔	Poor ↔			**Outbreaks of disease, introduced species and pest species:** Outbreaks of disease are localised and patchy across the Region. Although pest control programs have been successful on local scales, introduced species continue to be recorded. Other outbreaks, such as *Trichodesmium,* have increased, but data are limited on a broad scale. The severity of the crown-of-thorns starfish outbreak continues to seriously affect coral reef habitats.
Good	Good ↔	Good ↔	○	○	**Outbreaks of disease:** The incidence of disease is localised and patchy across the Region. Disease has affected corals, turtles, dolphins, coral trout and prawns since 2014. Reports of coral disease peaked following mass bleaching events in 2016 and 2017. Incidence of disease will increase with global warming.
Poor	Very poor ↓	Very poor ↔	●	●	**Outbreaks of crown-of-thorns starfish:** The Region is still experiencing an outbreak of crown-of-thorns starfish which began around 2010, seriously affecting ecosystem function in many areas. The areas most heavily affected by starfish predation have shifted from reefs offshore of Cairns to those south of Innisfail, with the Swain Reefs also experiencing significant impacts.
Good	Good ↔	Good ↔	○	○	**Introduced species:** Eradication of certain introduced species on a number of islands has been confirmed since 2014, and other infestations are being effectively managed. New incursions of introduced marine species in the Region have not been recorded since 2014.
Good	Good ↔	Good −	◐	○	**Other outbreaks:** Outbreaks of some species are likely to have resulted from declining ecosystem conditions. *Trichodesmium* blooms are increasing in particular areas, whereas *Drupella* predation appears similar to levels seen before 2014.

3.8 Overall summary of ecosystem health

The condition of the Region depends on a range of chemical, physical and ecological processes, the health of connected coastal ecosystems, and impacts of disease and pest outbreaks. Of the 31 ecosystem health components assessed across those five areas, about 60 per cent remain in good to very good condition; the rest are in poor to very poor condition. Eleven of the 31 components have deteriorated since 2014, mainly due to declines in ecological processes (such as symbiosis and recruitment) and changes to some physical processes (such as sea temperature and light).

Exposure to both acute and chronic disturbances, such as record high sea temperatures and poor water quality, have contributed to an overall decline in ecosystem condition, with both ecological and physical processes assessed as deteriorating

The decline in ecosystem condition in the Region over the past five years has been exacerbated by both acute and chronic disturbances, such as record high sea temperatures and poor water quality. Extreme sea temperatures caused by global warming have had the greatest impact: heat stress has caused unprecedented loss of coral reef habitat along two-thirds of the Reef and had flow-on impacts on dependent species. The unprecedented chronic and acute spikes in sea temperature across much of the Region have driven the change in grade for sea temperature from poor to very poor. Sea temperature and other physical and chemical processes (such as sea level and ocean pH) will continue to deteriorate as the effects of climate change accelerate. Other physical processes, such as sediment exposure and freshwater inflow, have remained stable since 2014.

Extreme thermal stress in 2016 and 2017 underscored the deterioration of sea temperature to very poor. The effect has influenced the deterioration of symbiosis and reef building

Apart from ocean pH, which has deteriorated since 2014, chemical processes are relatively stable: ocean salinity is unchanged and nutrient cycling remains in poor but stable condition. Although some improvements are being made in land management practices to reduce nutrients and sediments from land-based run-off, there are significant time lags between changes in management and improvements in marine processes (Section 6.5).

Ecological processes, including microbial processes, particle feeding, primary production and competition remain poorly understood. The loss of some coral habitats in 2016 and 2017 has affected some key ecological processes, particularly those associated with coral, such as particle feeding, primary production, recruitment and reef building. The deteriorating condition of many ecological processes has affected the integrity of the Region's outstanding universal value.

Some processes important to replenishment and recovery of species and habitats, such as currents, connectivity and primary production remain in good to very good condition

Coastal ecosystems that support the Reef remain in poor condition overall. However, the trends of most components have stabilised. Woodlands and forests is the only coastal ecosystem type that continues to deteriorate following a further reduction in its extent. Continued modification of coastal ecosystems will increase sediment inflow, reduce connectivity to the Reef and reduce capacity of these habitats to support the Region's ecosystems and species.

Outbreaks of crown-of-thorns starfish persist in the Region, especially affecting offshore reefs from Innisfail and Townsville. A more recent outbreak has been identified in the Swain Reefs. The severity of these outbreaks continues to reduced live coral reef habitat. Programs to eradicate introduced pests have been successful on some islands.

Reefscape during the 2016 mass coral bleaching event. Some bleached corals appear white, while others appear fluorescent. © GBRMPA