

**Faculté des bioingénieurs**

# **Deriving a habitat quality index to inform reef conservation in the Great Barrier Reef**

How to identify and quantify the main threats to coral reefs

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# Abstract

The Great Barrier Reef, as the world's largest coral reef ecosystem, is an exceptional site of global importance. Unfortunately, after thousands of years of existence, this wonderful biodiversity place, which shelters no less than 600 coral species and 1600 fish species, is under severe threats.

The main threat is climate change. It induces a rise in seawater temperature which causes bleaching events. In addition, we are witnessing an increase in the frequency of destructive tropical cyclones. Human activities along the coasts bordering the GBR are also responsible for the degradation of this vast marine ecosystem. Agricultural activities discharge many pollutants into the ocean that degrade water quality. The many COTS outbreaks that ravage some reefs are also a significant concern to be considered.

The aim of this thesis is to develop indices to understand, identify and quantify the main threats. First, single-threat indices are developed for each of them. Those indices have been designed to provide an estimate of coral cover loss. Then, we combine them to obtain a global reef-level habitat quality index for the entire GBR. The contribution of each threat in the global index will be deduced from coral cover data.

The habitat quality index can be used to improve estimates of connectivity between reefs to obtain a closer-to-reality connectivity. Most of the indices presented in this thesis have the advantage of giving an annual indication of the impact of the threats. They therefore allow us to monitor the evolution of the state of the GBR. This could help decision-making, particularly for the creation of protected areas.



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# Acronyms

**AIMS** Australian Institute of Marine Science.

**BoM** Bureau of Meteorology.

**CDI** Cyclone Damage Index.

**COI** COTS Outbreak Index.

**COTS** crown-of-thorns starfish.

**CRW** Coral Reef Watch.

**DHW** degree heating week.

**DIN** dissolved inorganic nitrogen.

**GBR** Great Barrier Reef.

**GBRMPA** Great Barrier Reef Marine Park Authority.

**HQI** Habitat Quality Index.

**LPI** Land-based Pollutants Index.

**NI** Nutrient Index.

**NOAA** National Oceanic and Atmospheric Administration.

**PI** Pesticide Index.

**PN** particulate nitrogen.

**PP** particulate phosphorus.

**PSII** photosystem II.

**SI** Sediment Index.

**SST** sea surface temperature.

**TC** tropical cyclone.

**TSI** Thermal Stress Index.

**TSS** total suspended sediment.

# 1 Introduction

## 1.1 The Great Barrier Reef

Located off the east coast of Queensland in north-east Australia, the iconic Great Barrier Reef (GBR) is the world's largest coral reef ecosystem, containing more than 3,800 individual coral reefs. Spanning roughly 2,600 km in length and up to 200 km in width, the GBR covers an area of about 344,000 km<sup>2</sup>. Visible from space (Fig. 1), it is the largest living biogenic structure (created by living organisms) on Earth, built by billions of tiny organisms, known as coral polyps. This large ecosystem is home to many marine species, including about 600 coral species and 1600 fish species. In 1981, GBR was made a *UNESCO World Heritage Site* (De'ath et al., 2012).

Unfortunately, this wonderful ecosystem has been severely damaged by different stressors. Many scientists around the world are concerned about the rapid degradation of coral reefs (Johnson et al., 2017; Wenger et al., 2017; Hughes et al., 2018). The most severe disturbances are mass coral bleaching, crown-of-thorns starfish (COTS) outbreaks, land-based pollutants from runoff, tropical cyclones and coral diseases (De'ath et al., 2012). Professor Terry Hughes, one of the world's leading experts on coral reefs, made an alarming assessment of the state of the world's corals in the renowned journal *Nature*:

«Reefs are degrading rapidly in response to numerous anthropogenic drivers. In the coming centuries, reefs will run the gauntlet of climate change, and rising temperatures will transform them into new configurations, unlike anything observed previously by humans. Returning reefs to past configurations is no longer an option. Instead, the global challenge is to steer reefs through the Anthropocene era in a way that maintains their biological functions. »  
(Hughes et al., 2017)

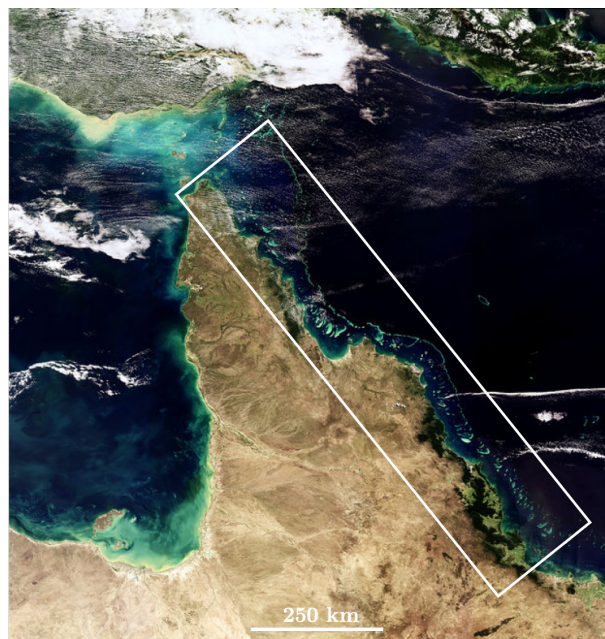


Figure 1: This image, from the ENVISAT satellite, shows the full extent of the GBR, located off the east coast of Queensland, Australia. *Credit: ESA.*



## 1.2 Protecting the Great Barrier Reef

Coral reefs can be seen as the rain forests of the sea, they are among the «most productive and biologically diverse ecosystems on Earth »(Odum & Odum, 1955). Despite the fact that only 0.1% of earth surface is occupied by coral reefs in the world, (Reaka-Kudla, 1997; Spalding & Grenfell, 1997), 35% of all marine species depend on them (Reaka-Kudla, 2005). They provide valuable ecosystem benefits to vast numbers of coastal communities. They are important sources of food and income, for example as nurseries for commercial fish species or with tourist activities such as diving and snorkelling. Coral reefs also play an important role in protecting shorelines from destructive waves generated by storms. In addition to this, coral reefs could provide treatments for diseases such as cancer, HIV, malaria and other diseases. The potential for new pharmaceutically valuable discoveries is still vast (Burke et al., 2011).

According to Wilkinson (2008), half a billion people worldwide rely directly or indirectly on goods and services they provide. Among these people are the Aboriginal people, the first Australians. More than 70 Aboriginal groups have long, continuing relationships with the Great Barrier Reef region and its natural resources. Protecting the GBR is therefore also essential to preserve their cultural practices (GBRMPA, 2019).

A report written by Deloitte Access Economics (2017) highlights the economic value of GBR for Australia. According to this report «The Great Barrier Reef has a economic, social and icon asset value of \$56 billion. It supports 64,000 jobs and contributes \$6.4 billion to the Australian economy in 2015-16. »Nearly 90% of this economic contribution (approximately \$5.7 billion) is from tourism activities alone. This sector employs around 59,000 people. Commercial fishing and aquaculture production, recreational activity and scientific research and management represent the other 10%.

The Great Barrier Reef Marine Park (GBRMP) is a multiple-use area established in 2004 and covering 344,000 km<sup>2</sup>. Zones have been defined in accordance with the *Great Barrier Reef Marine Park Zoning Plan 2003* (Fig. 2) and help to manage and protect the values of the Marine Park by defining what activities can occur in which specific areas. The Marine Park is divided into 8 different types of zones each having a different level of protection from the least protected, ‘*General Use Zones*’, up to the most restrictive, ‘*Preservation Zones*’. To facilitate zone identification, a specific color has been assigned to each zone. The major zones are:

- General Use Zone (*Light Blue*, 34%) : all activities allowed, in a reasonable way
- Marine National Park Zone (*Green*, 33%) : ‘no-take’ area – extractive activities (e.g. fishing, collecting) not allowed
- Habitat Protection Zone(*Dark Blue*, 28%) : potentially damaging activities (e.g. trawling) not permitted
- Conservation Park Zone (*Yellow*, 1.5%) : extractive activities allowed with additional restrictions

Other zones represent less than five percent of the Marine Park. They include Preservation (*Pink*), Scientific Research (*Orange*), Buffer (*Olive Green*) and Commonwealth Island Zones. (GBRMPA, 2019)

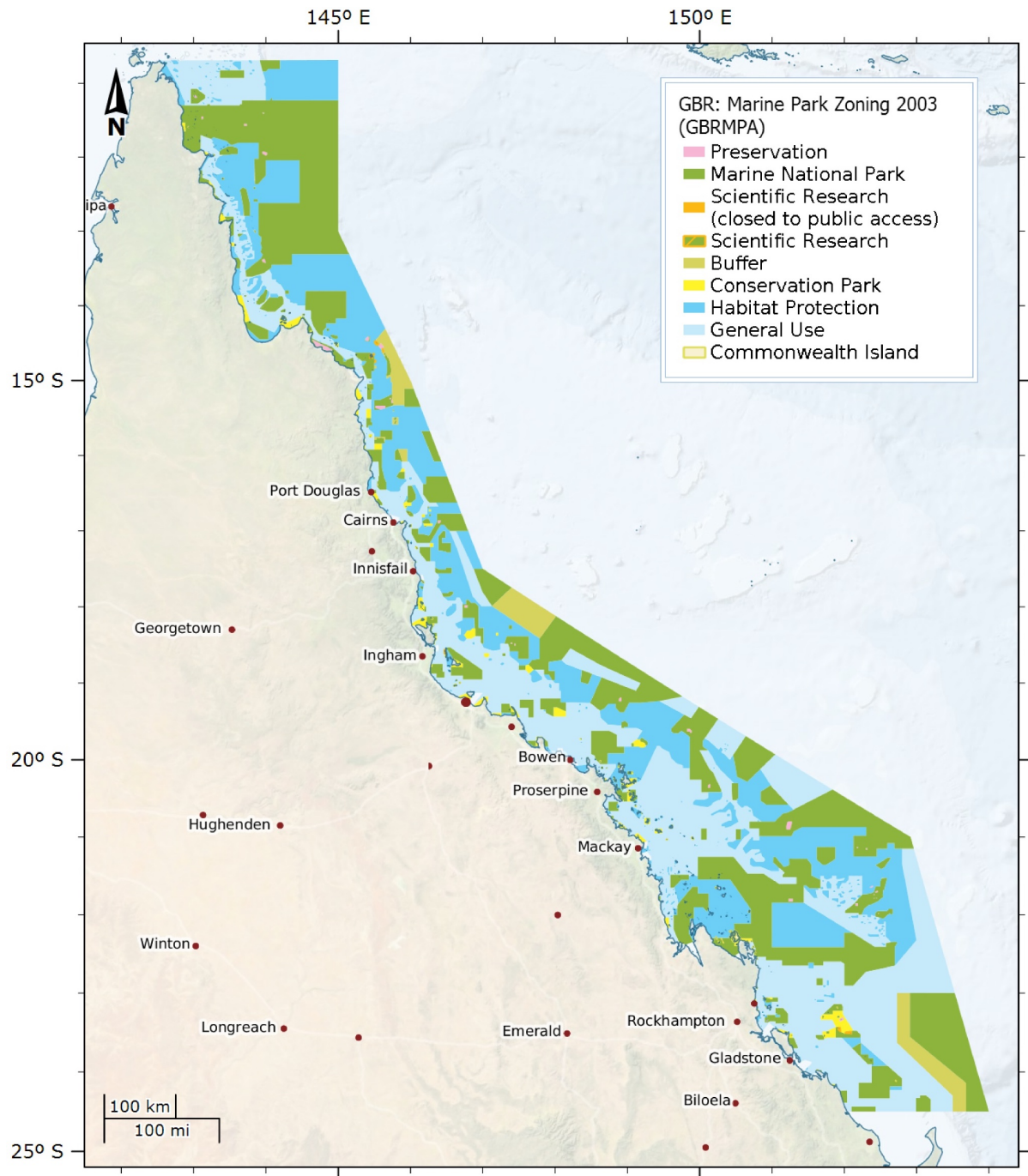


Figure 2: Great Barrier Reef Marine Park Zoning 2003. For each of the 8 zones, a specific colour is assigned. *Credit: Zoning © Commonwealth of Australia (Great Barrier Reef Marine Park Authority).*

### 1.3 Coral reproduction

Over time, many corals have evolved with the ability to reproduce both asexually and sexually. Asexual growth is done by budding or fragmentation. Budding occurs when new clonal polyps bud off from parent polyps. This mode of reproduction allows the expansion or beginning of new colonies (Sumich, 1996). The other mode of asexual reproduction is fragmentation. Coral fragments can detach from the colony and if they fall on a

favourable substrate can develop and spread. (Veron & Stafford-Smith, 2000). Although this phenomenon occurs most often naturally by wave action, humans can also purposely detach coral fragments to make them grow elsewhere (Highsmith, 1982).

Concerning the sexual reproduction of corals, there are 2 modes of reproduction : (1) broadcast spawning and (2) brooding. Broadcast spawners release a massive number of eggs and sperm into the water (Fig. 3b), where those gametes will combine to form planktonic larvae, also called planulae (Veron & Stafford-Smith, 2000). By contrast, brooding coral species have internal fertilization and embryogenesis before releasing settlement competent planulae (Foster & Gilmour, 2018). As a result, brooders release fewer larvae but they are larger and better-developed compared to broadcast spawners (Veron & Stafford-Smith, 2000). According to Harrison (2011), «there are far fewer brooding coral species than broadcast spawning species, with approximately 83% employing broadcast spawning, 14% employing brooding and 3% using both modes (of the 428 stony coral species for which reproductive mode is known) ».



(a) Many coral species spawn by releasing millions of eggs and sperm into the water at the same time. *Credit: Emma Hickerson.*



(b) A male star coral (*Montastraea cavernosa*) releases sperm into the water column. *Credit: Brendan Holland.*

Figure 3: Sexual reproduction of broadcast corals

Broadcast spawning species generally have only one long gametogenic cycle per year. This one can last between 5 and 7 months and after that they release their eggs and sperm in mass spawning events (Shlesinger et al., 1998; Harrison, 2011). Because reefs are sometimes far from each other, and obviously cannot move, it is important that they release their gametes at the same time (Fig. 3a) (Veron & Stafford-Smith, 2000). In the GBR, about a quarter of coral species spawns at the same time during a few nights in spring or early summer (Willis et al., 1997). These few nights, when the water is warmer and the winds less strong, correspond to the optimal environmental conditions for fertilization, survival and larval settlement (van Woesik R., 2010; Foster et al., 2018). On the other hand, brooding species have multiple gametogenic cycles per year. These cycles are shorter and last approximately 3 months. Therefore breeding seasons range from several months to continuously throughout the year (Shlesinger et al., 1998; Harrison, 2011). Since brooders can store unfertilized eggs for weeks, they therefore require less synchronization for fertilization (Veron & Stafford-Smith, 2000).

## 1.4 Connectivity

Connectivity in GBR, as in many coastal marine ecosystems, occurs mainly through larval dispersal (Thomas, 2015). During the first stages of coral larvae'life, when the larvae behavioural capacity is not sufficiently developed, they follow currents in order to move (Underwood et al., 2013). Water circulation is therefore essential for coral reproduction and survival. Within the GBR, it is strongly influenced by 3 factors which are tides, wind and exchanges with the nearby Coral Sea (Brinkman et al., 2002; Wolanski et al., 2003; Wolanski & Pickard, 1985), however their importance can vary according to space and time.

Studying larval dispersal is therefore essential to understand how coral reefs are connected to each other. Scientists use the term “*connectivity*” when different populations of a species are connected to each other through the dispersal of individuals such as larvae, juveniles or adults (Sale et al., 2005). For corals, a sessile species, connectivity is realized only by dispersal of larvae. However, all larvae released by a reef will not always be able to settle and develop in a new population. If the environmental conditions are too bad or if there is no space available, some of the larvae will not be able to settle and will eventually die. The process by which a larva successfully develops in a host population is known as “*recruitment*” (Thomas, 2015).

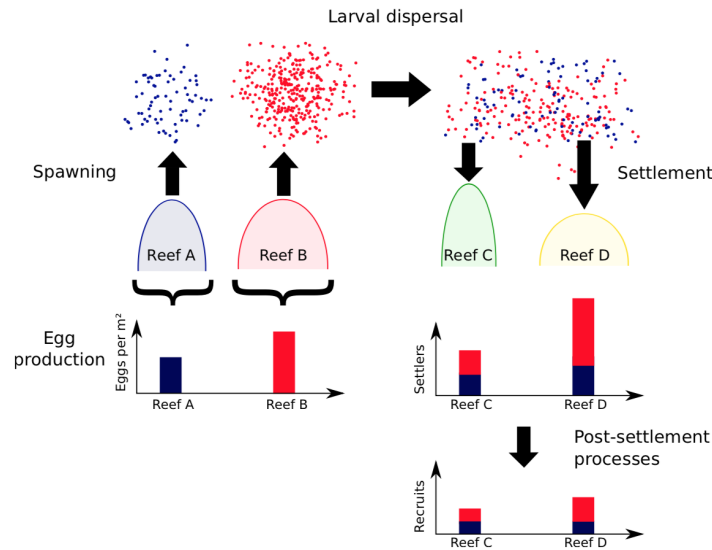


Figure 4: Illustration of the process of population connectivity through larval dispersal. *Credit: Thomas (2015).*

When we talk about connectivity, we must therefore be careful about what is taken into account in models or calculations. Indeed, most numerical models focusing on larval dispersal ignore recruitment. In this case, we will talk about *potential* connectivity, which provides information on the potential of populations to be demographically connected. On the other hand, the *realised* connectivity will take into account the success of larval recruitment by adding information on habitat quality or available reef space (Burgess et al., 2014; Thomas, 2015).

Connectivity between habitats is very important for many reasons. Firstly, it allows species to colonize new habitat patches. Secondly, it allows the recovery of habitats that



have been damaged by disturbances (e.g. bleaching or tropical cyclones which can destroy large areas of coral). Well-connected reefs will receive more larvae from many sources and may be more resistant to disturbance (Cowen et al., 2006). And finally, it allows genetic mixing between distant populations, which is beneficial for adapting to environmental changes (Salm & Coles, 2001). Maintaining good connectivity patterns is therefore essential to ensure population recovery, persistence and resilience both within and between protected areas (Underwood et al., 2013). Hence, spatial management strategies, such as Marine Protected Areas, must incorporate connectivity knowledge into their design.

## 1.5 Threats to the GBR

Corals are very sensitive to environmental conditions. To thrive successfully, they need clear, warm and nutrient-poor waters. They also require plenty of light so that the symbiotic micro-algae in their tissues can photosynthesize (Burke et al., 2011). If water quality deteriorates, corals are directly threatened. Most scientists usually classify human pressures on coral reefs into 2 categories (Table 1). *Local* threats come from human activities near reefs, which have a direct and relatively localized impact. Whereas *global* threats are those that affect reefs indirectly, through human impacts on global climate and ocean chemistry. For example, we can observe an increase in the frequency of severe cyclones due to climate change.

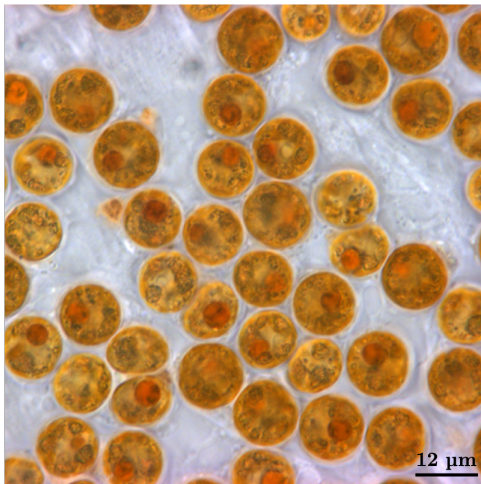
| Local threats                       | Global threats      |
|-------------------------------------|---------------------|
| Coastal development                 | Thermal stress      |
| Land-based pollution                | Cyclone damage      |
| Marine-based pollution and damage   | COTS outbreaks      |
| Overfishing and destructive fishing | Ocean acidification |
|                                     | Coral diseases      |

Table 1: Threats to corals worldwide – threats used in this thesis are in red while threats not taken into account are in black.

Given the study area of this thesis, the Great Barrier Reef, some threats were chosen rather than others. Among the local threats, we will only work on the impact of land-based pollutants. In section 1.5.4, we will see that the Great Barrier Reef catchment area is mainly used for agricultural and grazing purposes. This generates large amounts of sediments, nutrients and pesticides that end up in the sea. In Australia, only 3.5 million people live within 30 km of a coral reef, it is the lowest coastal density of any coral regions (Burke et al., 2011). Due to the long distances between reefs and people, overfishing and coastal development threaten only 1% of reefs (Jackson et al., 2001). Marine-based pollution and damage is mainly caused by the many shipping lanes that cross the GBR. In reality, few reefs (about 10%) are only moderately threatened because maritime transport regulations are very strict and incidents are rare (GBRMPA, 2009). These local threats are therefore not taken into account in the framework of this thesis. Concerning global threats, we choose to focus our efforts on tropical cyclones, coral predation by COTS and bleaching. However, ocean acidification is also an important issue that would be interesting to consider. The following subsections will develop in more detail the 4 threats that are the subject of this thesis.

### 1.5.1 Coral bleaching

The symbiotic relationship between the coral polyp and its microscopic algae, zooxanthellae, is the key feature of coral reef settlement, growth and productivity. Zooxanthellae are single-celled photosynthetic dinoflagellates (Fig. 5a) living in the cells of polyps' endodermal tissues. These micro-algae are often found in gastrodermal cells and tentacles (Fig. 5b) where they find protection and shelter. (Levinton, 1995)



(a) Corals are densely populated by round micro-algae, called zooxanthellae. One to several million symbiotic cells can be found in an area of tissue the size of a thumbnail. *Credit: Todd C. LaJeunesse.*



(b) Zooxanthellae algae growing inside transparent corals result in the colorful variation of coral reefs. *Credit: greencareer.net.au*

Figure 5: Symbiotic relationship between coral polyp and zooxanthellae

Due to their symbiosis with zooxanthellae, the distribution and growth of coral polyps are highly dependent on light (Levinton, 1995). As a result, most coral reefs live in shallow waters, up to depths of about 60 - 70 meters, because beyond these depths there is a lack of light. In addition, corals also need clear water to allow light to pass through (Barnes, 1987).

Although some deep-sea and cold-water corals lack zooxanthellae due to their habitat, almost all reef-building corals possess them. Indeed, symbiotic algae improve the ability of coral to synthesize calcium carbonate, which is the building block of coral reefs. In addition to improving calcium carbonate synthesis, zooxanthellae fix large amounts of carbon during photosynthesis, some of which is transmitted to their host polyp. These energy-rich compounds may be used for metabolic functions and the manufacture of proteins, fats and carbohydrates (Lalli & Parsons, 1995).

For most corals, the symbiosis with zooxanthellae is not sufficient to cover all their energy needs. For example, they require nitrogen that is not provided in sufficient quantities by their symbionts. This nitrogen is found in the zooplankton that corals can catch with their tentacles. The dependence of corals for zooxanthellae depends on the species and the situation (Barnes, 1987). Some corals are almost entirely dependent on their symbiosis and obtain up to 95% of their energy needs through it. In the most extreme case of

heterotrophy, some species only get 50% of their energy requirements from zooxanthellae and must therefore find the remaining 50% in the capture of prey or particles (Barnes & Hughes, 1999). In general, corals are therefore strongly dependent on their zooxanthellae because they are essential for their survival.



Figure 6: This fire coral was severely bleached during the 2016 mass bleaching event in GBR. On the left, the brownish color is synonymous with healthy tissues because they reflect the presence of photosynthetic pigments of their symbiotic zooxanthellae. On the right, white coral skeleton shows through the translucent unpigmented coral tissue. *Credit: Richard Vevers.*

Under stressful conditions, the precious symbiotic relationship can break down. If sea temperature rises too high, zooxanthellae are unable to handle incoming light without generating harmful oxygen radicals. When this occurs, the relationship between coral and algae is disrupted, resulting in the degeneration of algae in tissues or their release into the sea. This phenomenon leads to a significant reduction of the zooxanthellae density in the coral tissue (Marshall & Schuttenberg, 2006). When this happens, we talk about bleaching because corals appear ‘bleached’. Indeed, as we can see on Fig. 6, coral’s coloration fades or turns pale, and the bright white coral skeleton is visible through the translucent unpigmented coral tissue (Glynn, 1996).

When corals are bleached, they do not die immediately. If favourable conditions return soon, zooxanthellae can repopulate bleached colonies in a few weeks or months. To some extent, corals can therefore survive bleaching events that are not too long (Glynn, 1996). However, the surviving corals are significantly weakened. As a result, they are likely to suffer reduced growth rates (Goreau & Macfarlane, 1990), decreased reproductive capacity (Ward et al., 2000), and increased susceptibility to diseases (Harvell et al., 1999). Unfortunately, if both the intensity and duration of thermal stress are too severe, bleaching can lead to coral death. According to Wilkinson (2004), in many cases of severe bleaching events, more than 90% of corals are killed.

In less than 10 years, the number and intensity of bleaching events have increased around the world (Fig. 7). It was only at the end of the 20th century that the whole world became concerned with the bleaching issue. In 1997-1998, the extreme El Niño/La Niña switches in the global climate in a catastrophic way. Increased sea surface temperatures associated to this phenomenon resulted in the most extensive coral bleaching and mortality ever recorded with approximately 16% of the world’s coral reefs being effectively destroyed (Wilkinson, 2008). Before this event, coral bleaching was considered to be only a local

problem. But since the magnitude of the 1997-98 event, a distinction has been made between mass coral bleaching and localized bleaching events due to the global extent of its impacts on reefs and reef regions (Marshall & Schuttenberg, 2006).

At a local scale, coral bleaching may be caused by a wide variety of factors. Among them are storms, sedimentation, changes in salinity or temperature and coral diseases. At a regional or global scale, the main cause of bleaching events is the rise in sea temperature (Brown, 1997). A sea temperature rise of 1-2 °C above the “long term average maximum” are sufficient to cause mass bleaching (Hoegh-Guldberg, 1999). The severity of bleaching is determined by both the intensity and duration of temperature anomalies. If temperatures are high, a short period of time may be sufficient to cause bleaching. While if they are lower, it will take longer to impact the corals (Jones et al., 1998).

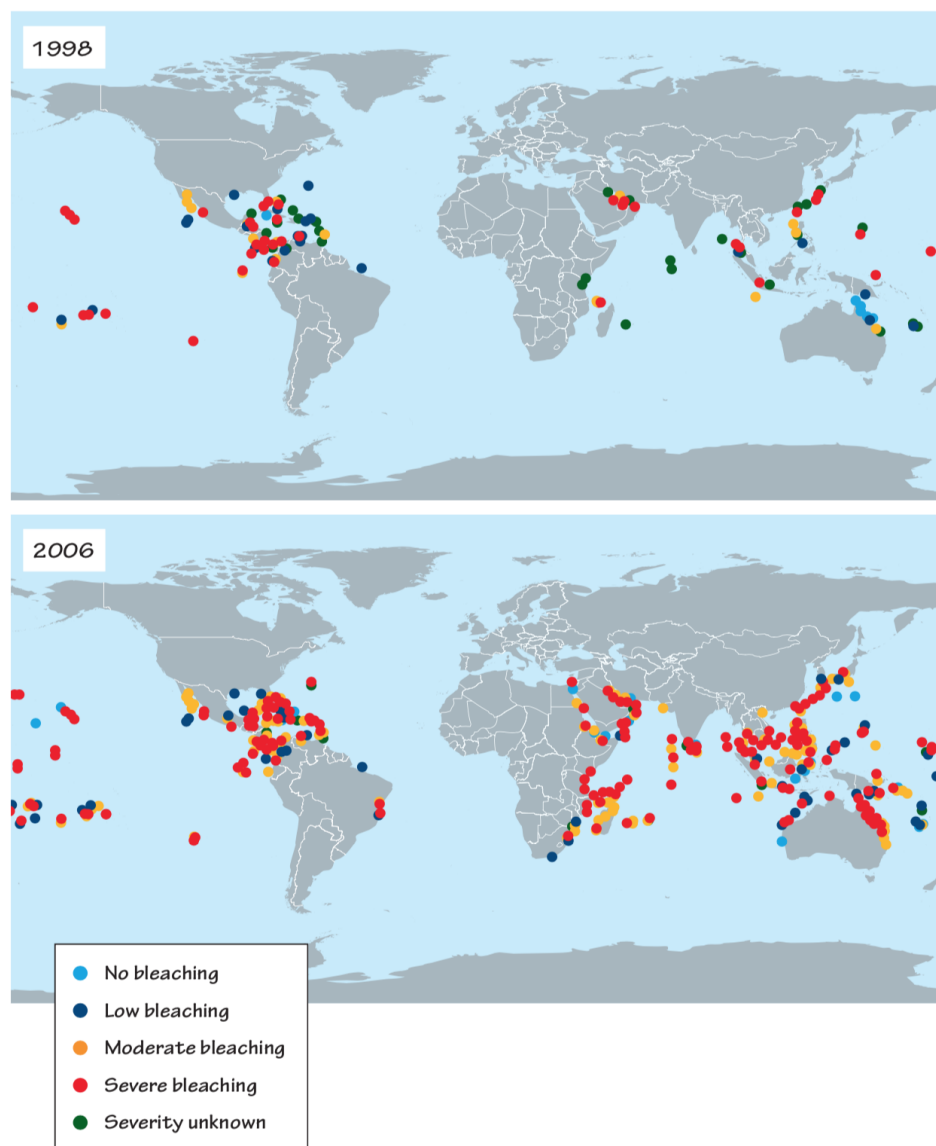


Figure 7: In less than 10 years, the extent and severity of mass coral bleaching events have increased worldwide. Since 1998, coral bleaching has become a common issue in almost all reef regions of the world. *Credit: Marshall & Schuttenberg (2006).*



This last paragraph gives an overview of the aspects that need to be worked on to preserve corals from bleaching. Two main factors are relevant to consider if we want to understand how coral reefs will evolve in the coming years in the context of bleaching:

1. the rate and extent of increased temperature stress (Hoegh-Guldberg, 1999) and
2. the resilience of coral reef ecosystems to bleaching (Hughes et al., 2003).

According to the first factor, to preserve coral reefs from bleaching, temperature anomalies should be fewer and less extreme. In other words, we should limit the increase in global temperatures. This is a huge challenge that must be managed by national and international policies. On the other hand, the second factor is easier to manage at a local scale. The ‘*Reef Manager’s Guide to Coral Bleaching*’ written by Marshall & Schuttenberg (2006) show that «four successive conditions determine the ultimate impacts of mass coral bleaching following a regional heat stress event, and each can be considered a potential focus for management action». These conditions, shown in Fig. 8 in brown, are bleaching resistance, coral tolerance, reef recovery and human adaptive capacity. Each of these is determined by a series of factors that, combined, influence the resilience or vulnerability of the coral reef ecosystem. Among the factors that can be improved by good management measures (in green on Fig. 8) we find connectivity. Indeed, biological diversity and connectivity among reefs are important considerations that promote reef recovery.

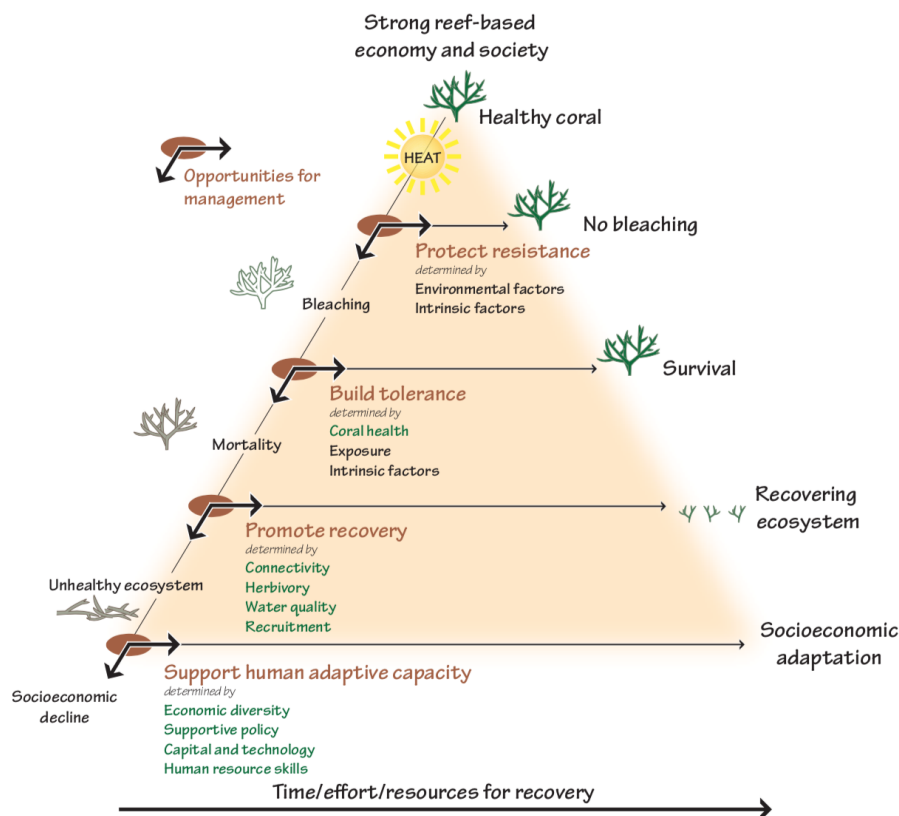


Figure 8: Opportunities to minimise mass coral bleaching impacts. Factors vary according to their potential for change through management interventions (in green – can be influenced by local management actions), their relative influence and the scale (coral, ecosystem or human community) at which they are expressed. Credit: Marshall & Schuttenberg (2006) adapted from Obura (2005).

### 1.5.2 Tropical cyclones

The Great Barrier Reef area is regularly exposed to the devastating forces of cyclones. The Great Barrier Reef Marine Park Authority (GBRMPA) (2011) reported 116 cyclones in the Marine Park between 1970 and 2006. Long term monitoring data collected by Australian Institute of Marine Science (AIMS) shows that approximately 34% of the total coral mortality recorded between 1995 and 2009 in GBR was attributable to cyclones and storms (Osborne et al., 2011). The most intense storms are considered particularly important in the dynamics and evolution of reef ecosystems, and their frequency seems to be increasing. For example, the last three decades have seen the frequency of severe cyclones (category 3-5) almost double (Webster et al., 2005).

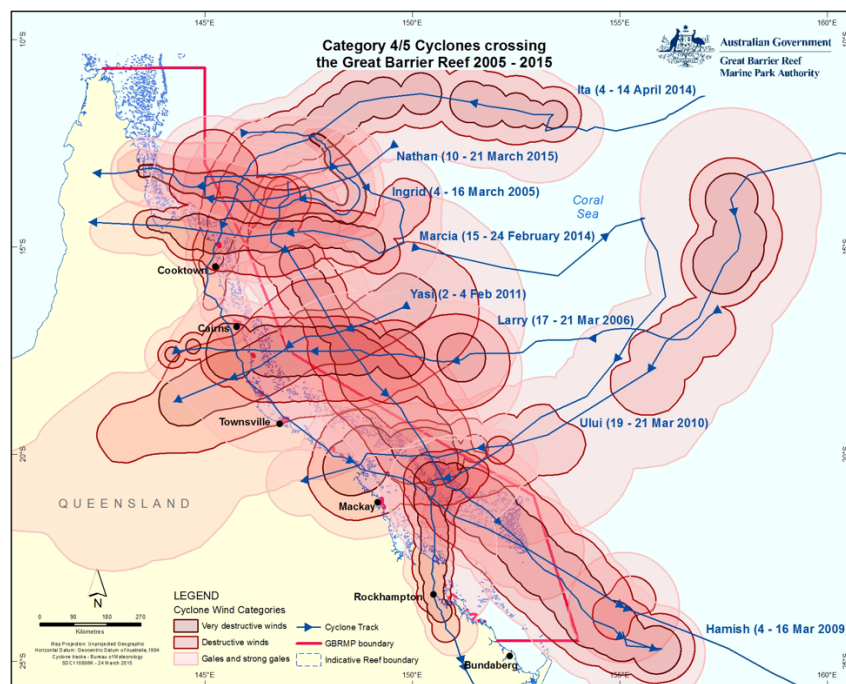


Figure 9: Extent of the Great Barrier Reef impacted by Category 4 or 5 cyclones in the 10 year period 2005-2015. *Credit: Spatial Data Centre, GBRMPA.*

Tropical cyclones (TC) can cause severe and widespread damage to coral reefs. According to Harmelin-Vivien (1994), there are 5 main types of damage to coral reefs:

- mechanical damage,
- damage due to changes in sedimentation processes,
- damage due to increased turbidity,
- damage due to decreased salinity,
- damage due to change in sea level.

Regarding mechanical damage, we can discern direct and indirect damage to corals. Direct damage occurs mainly as a result of the mechanical forces exerted by the waves and currents generated by extreme-velocity winds. Coral colonies may be fragmented by direct wave action, but they can also be uprooted, overturned and carried above sea level or into deeper water (Harmelin-Vivien, 1994). Direct mechanical effects occur mainly in shallow

water from 3 to 12 meters (Harmelin-Vivien & Laboute, 1986). Indirect mechanical damage is caused by the initial destruction of corals. During the passage of a cyclone, massive corals may detach from their substrates and start rolling long distances, which can sometimes damage still intact deeper colonies (Laboute, 1985; Done, 1992).

In addition to mechanical damage, cyclones can affect corals by changing sedimentation processes. Both broken corals and uprooted soft benthic organisms by cyclones generate an increase in coarse sedimentary material. On the other hand, cyclones can resuspend existing sediments (Gagan et al., 1988). These sediments, as they move from one area to another, may bury and kill benthic organisms such as corals (Hubbard et al., 1991).

Cyclones are often synonymous with heavy rainfall that carries water loaded with land-based sediments into the ocean. These sediments are added to those already present in the ocean and resuspended by intense water movements. Water turbidity therefore increases and can cause a decrease in coral growth or even kill them. Indeed, high water turbidity reduces the amount of light reaching corals which is essential for photosynthesis of zooxanthellae micro algae (see section 1.5.1) (Rogers, 1983).

Torrential rainfall and river flooding associated with cyclones can lead to extensive flood plumes and rapidly reduce surface salinity. The rapid fall in salinity has very negative impacts on coral health. Indeed, mass bleaching episodes have already been reported in response to lower salinity. Sometimes this leads to the death of coral colonies living in shallow waters. (Stephenson et al., 1958; Goodbody, 1961; Stoddart, 1969).

And finally, cyclones can cause sea level changes. Cyclones cause low pressures which can lead to a sea level fall. Depending on weather conditions, the sea level fall can vary from several days to several weeks (Glynn, 1990; Coffroth et al., 1990). According to Moorhouse (1936), corals exposed to prolonged emergence following tropical storms may die. This occurs mainly on reef flats and lagoons.

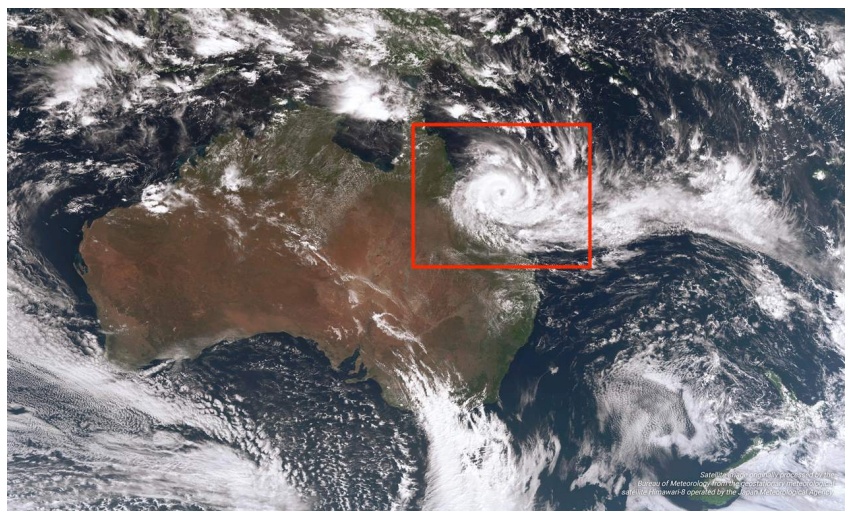


Figure 10: Weather satellite image of Tropical Cyclone Debbie. *Credit: BoM.*



### 1.5.3 Crown-of-thorns starfish outbreaks

Corals are vulnerable to predation; numerous species, such as parrotfish, crabs and gastropods, prey on coral polyps, destroying the substrate in the process and preventing other corals from settling. Among coral predators, one causes particularly devastating effects. This predator is the crown-of-thorns starfish (*Acanthaster planci*) also called coral-eating starfish (Jones & Endean, 1976).

Crown-of-thorns starfish (COTS), a multirayed starfish, is named for its helmet of long, sharp, mildly venomous spines. The species reaches a maximum diameter of 60 cm and adult specimens in GBR possess mainly 16 arms (Jones & Endean, 1976). However, according to Great Barrier Reef Foundation (2019), COTS spanning more than 1 meter have already been reported. COTS feed by attaching themselves to a coral head, extruding their stomachs out from their bodies, and digesting the underlying coral tissue with enzymes. When it

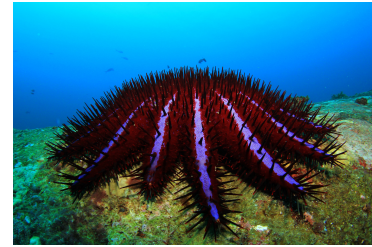


Figure 11: Crown-of-thorns starfish. Credit: DeeperBlue.

detaches, it leaves behind a large, white, dead skeletal patch that is rapidly colonized by filamentous algae as shown on Fig. 12. (Barnes & Hughes, 1999) COTS prey on nearly all corals, and can eat their way through 10 square metres of it a year. This is partly due to their high travel speed, up to 20 meters an hour. Moreover, COTS are difficult to control because they reproduce very quickly. A large female COTS can produce up to 65 million eggs in one spawning season (GBR Foundation, 2019).

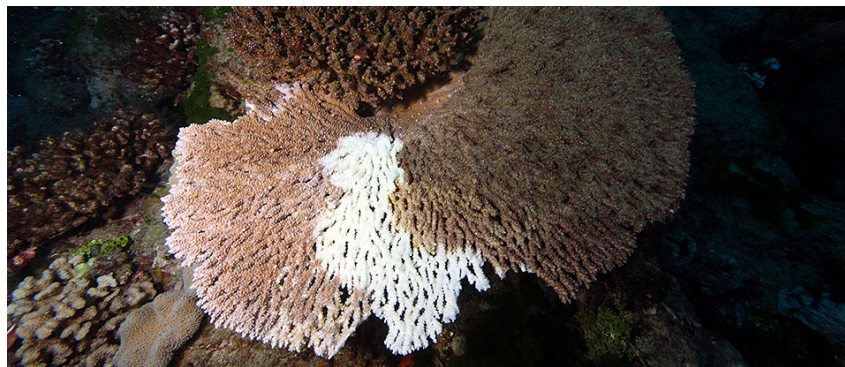


Figure 12: The middle section (white) part of the coral has been destroyed by a crown-of-thorns starfish. Blue-green algae is seen growing over dead portions of the coral on the right. The left side of the coral still contains living tissue. Credit: Greg McFall, NOAA Dive Program.

When COTS outbreaks occur at low densities, coral colonies can recover relatively easily (Barnes, 1987). However, if 30 COTS are found in a one hectare area, it is called an outbreak. In the 1970s, the northern GBR saw an outbreak of the scale of 1,000 COTS per hectare (GBR Foundation, 2019). At the same time, a devastating COTS outbreak killed 80 percent of the coral on American Samoa's reefs. A few years later, in 2012, the COTS population also exploded, destroying essential fish habitat and causing negative long-term effects on local fisheries (NOAA, 2019). According to AIMS (2019), in the past 40 years, three waves of COTS outbreaks have had a major impact on the GBR reefs. The most recent outbreak episode started in 2011 and is currently spread along parts of

the GBR.

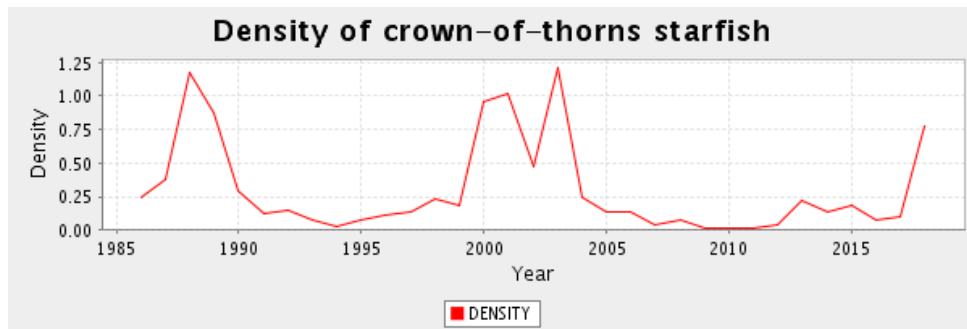


Figure 13: Time-series plot of the density\* of COTS on reefs across the GBR (\*density = mean number of COTS per 2 min. manta tow). *Credit: LTMP manta tow data 1986-2018, AIMS, 2019.*

According to NOAA, land-based pollution and the subsequent runoff of nutrients like nitrogen and phosphorus are believed to cause most COTS outbreaks. The elevated nutrient levels cause an increase in phytoplankton, which is the main food source for COTS larvae. This enables a much higher than usual number of larvae to survive and develop into juvenile COTS at which stage they start feeding on coral (AMPTO, 2019). Another cause for heavy outbreaks is the removal of the natural starfish's predators in many areas, particularly the overfishing of giant triton snail (Barnes & Hughes, 1999; Jones & Endean, 1976).

According to the *Great Barrier Reef Blueprint for Resilience*, «COTS control as one of the most feasible actions to reduce coral mortality and improve resilience on the GBR ». The first broad-scale, government-funded COTS control program began in 2012. Among methods for undertaking COTS control, the best one is to use a "modified drench gun to inject bile salts or household vinegar into the starfish" (Fig. 14). These injection methods have the advantage of minimizing risks of breaking corals and being safer than manual removal (GBRMPA, 2017). Due to the large number of reefs in Marine Park, it is essential to target priority reefs for control action. These reefs have been identified based on their connectivity and their current coral cover, among other things (GBRMPA, 2019).



Figure 14: Divers inject the central disk near an arm of each starfish with bile salt, a natural substance that kills the creature but does no harm to the reef. *Credit: Greg McFall, NOAA Dive Program.*

### 1.5.4 Land-based pollutants

The Great Barrier Reef Marine Part Authority (2019) states that “declining marine water quality from land-based run-off is one of the most significant threats to the long-term health and resilience of the GBR.” There is general consensus that excessive amounts of sediment, nutrients, pesticides and other pollutants have an impact on the ecological health of the GBR (McCulloch et al., 2003; De’ath et al., 2012).

Land-based run-off come from six natural resource management regions and 35 major catchments which drain 424,000 square kilometres of coastal Queensland (Fig. 16). We can classify catchments into 2 types. The first are small coastal catchments that provide a continuous flow of fresh water to the reefs. They are often supporting intensive agriculture. The second are the large catchments draining vast areas of inland grazing. They tend to be seasonal and influenced by flooding (GBRMPA, 2019). The ‘Great Barrier Reef catchment area’ is mainly used for grazing and agricultural purposes (Fig. 15). Changes in land use, urbanisation, agriculture and flood events have a major impact on the pollutant river’s loads and therefore indirectly on the health of coral reefs.

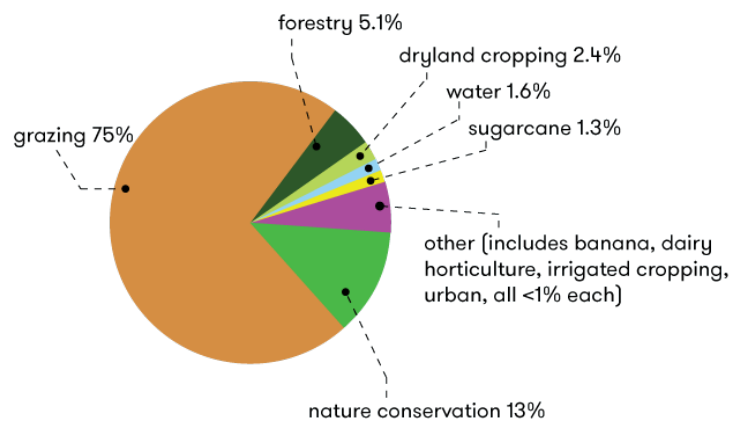


Figure 15: The 424,000 square kilometre catchment area of the Great Barrier Reef is mainly used for grazing and other agricultural purposes. *Credit: Australia Academy of Science.*

The 2017 Scientific Consensus Statement states that the greatest risk to water quality in the GBR depends mainly on discharges of nutrients, fine sediments and pesticides (Table 2). In the scientific literature, it is common to group them under the name ‘land-based pollutants’.

|                   |                                                                                                                                                                           |
|-------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Sediments</b>  | <ul style="list-style-type: none"> <li>- reduce the light available to inshore coral reefs</li> <li>- smother corals</li> </ul>                                           |
| <b>Nutrients</b>  | <ul style="list-style-type: none"> <li>- additional stress factor for corals</li> <li>- promote COTS population outbreaks</li> <li>- promote macroalgal growth</li> </ul> |
| <b>Pesticides</b> | <ul style="list-style-type: none"> <li>- pose a toxicity risk to freshwater ecosystems and some inshore and coastal habitats</li> </ul>                                   |

Table 2: Risk of land-based pollutants to corals

The second chapter of the 2017 Scientific Consensus Statement provides an up-to-date review of the state of knowledge relating to the source of land-based pollutants delivered to the GBR from adjacent catchments. The following 3 paragraphs provide an overview of the importance and source of pollutants.

- **Sediments.** Over the 9900 kt/yr of sediment discharged into the GBR, it is estimated that 80% are anthropogenic and due to land use changes. This represents a five fold increase as compared to pre-European conditions. The primary source of sediment (90% to the end-of-catchment loads) is due to gully, streambank and hillslope erosion. Poor land cover and surface condition within grazing areas made them the dominant land-use contributing sediment.
- **Nutrients.** Catchment modelling estimates that there is around 55 kt/yr of total nitrogen and 13.4 kt/yr total phosphorus delivered to the GBR. Approximately, 52% of total nitrogen and 66% of total phosphorus is estimated to be anthropogenic and due to land use changes. Studies on the effects of nutrients on GBR focus mainly on 3 forms of nutrients dissolved inorganic nitrogen (DIN), particulate nitrogen (PN) and particulate phosphorus (PP). Intensive cropping, such as sugarcane farming, are directly responsible for increased DIN loads. Sub-surface soil erosion in the grazing lands may contribute high loads of PN and PP depending of the soil type. Wastewater discharges from urban land uses can also generate loads of nutrients which can be important at local scales, but relatively minor in comparison to agriculture (<7% overall).
- **Pesticides.** Prevalent pesticides in GBR are photosystem II-inhibiting herbicides (PSII). Their mean annual loads are estimated to be approximately 12,000 kg/yr across the GBR. The highest concentrations are generally detected in smaller catchments with a high proportion of sugarcane.



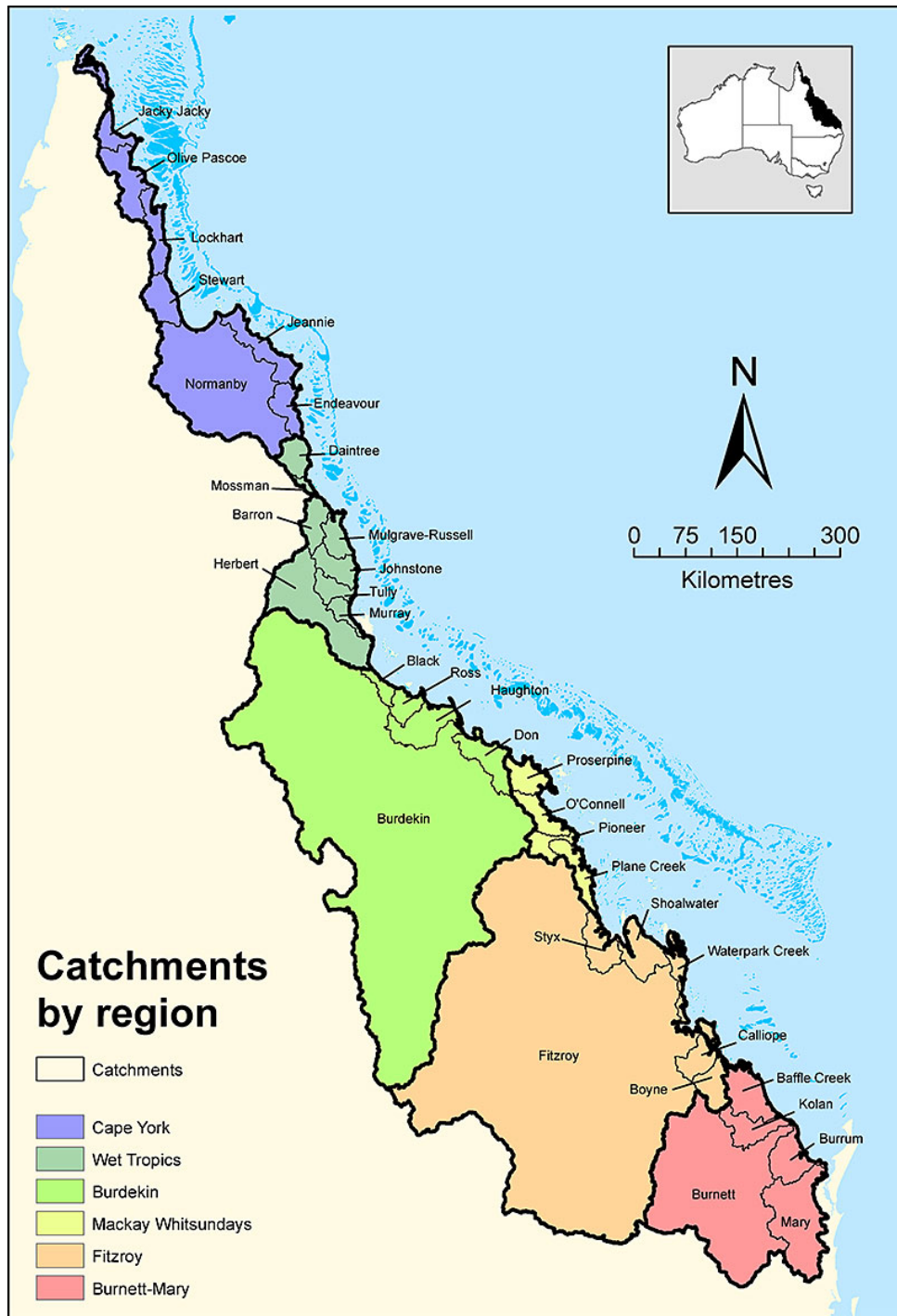


Figure 16: The GBR receives runoff from six natural resource management regions and 35 catchments, which drain 424,000 square kilometres of coastal Queensland. *Credit: Reef 2050 Water Quality Improvement Plan.*



## 1.6 Quantify reef habitat quality

There are many dangers to coral reefs worldwide. To build a global index to quantify the reef habitat quality, we have chosen to focus on the 4 main threats highlighted in the previous section. There are several reasons for this choice not to consider all the threats that impact GBR. The first reason is the risk of overfitting the model. If we want to add too much information in the model, we may do worse than well. Not taking into account secondary threats such as the impact of coastal cities is therefore a voluntary choice. The second reason is that by choosing to work on the main threats, we ensure that we are working on highly studied topics. As a result, many recent data sources and documentation are available for these threats.

Fig. 17 represents the 4 major hazards to GBR that will be used to create the global habitat quality index.

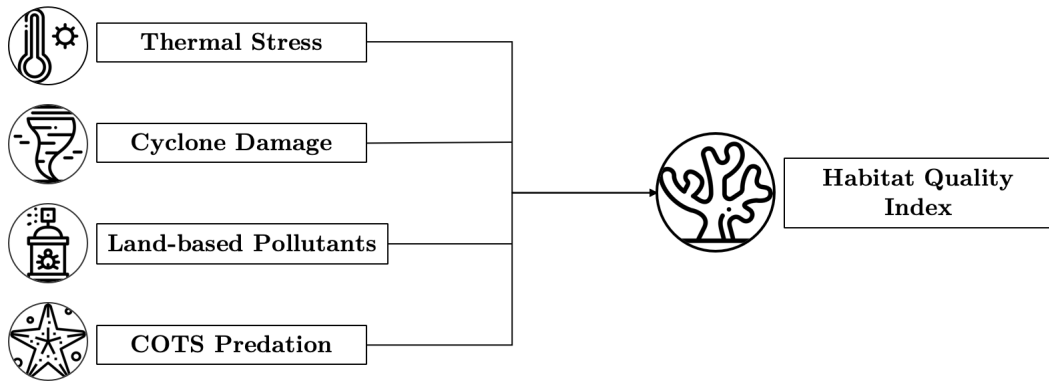


Figure 17: Major threats used to build Habitat Quality Index

Achieving quantified reef habitat quality is very useful to improve protection and conservation of this huge and fragile ecosystem. Due to its size, it is difficult both materially and financially to protect the entire GBR. It is therefore necessary to identify the areas where reefs are most threatened in order to possibly define protected marine areas.

Another way to protect the GBR ecosystem is to identify key reefs that ensure the persistence and the resilience of the entire GBR. These reefs can be seen as “*robust sources*”, i.e. reefs with high connectivity and reduced chance of being affected by disturbances.

High-resolution larval dispersion simulations identify the reefs most likely to support coral recovery due to their high connectivity. The aim of this thesis is to identify the reefs that are likely to be the least exposed to threats, in other words, the areas of the GBR with the best habitat quality.

By combining the results obtained in this thesis with connectivity data, it is now possible to identify reefs that are not only likely to be good sources by being well-connected, but are also able to provide the necessary larval supply by having enough adult breeders. This idea of combining habitat quality and connectivity has already been mentioned by Hock et al. (2017).

This information on the location of “*robust sources*” can help in decision-making to allocate management resources and prioritize sites important for the resilience of the entire reef system.

## 2 Material and Methods

The objective of this thesis is to convert the main threats to coral reefs in the GBR into a series of indices in order to obtain a single indicator of coral habitat quality. In the previous section, we identified 3 main global threats : coral bleaching, tropical cyclones and COTS outbreaks. According to De'ath et al. (2012), all these threats together are responsible for almost all of the loss of coral cover. In addition to these threats, we also observed that GBR was suffering from the many Queensland agricultural practices that release large amounts of pollutants into the ocean.

This section explains the material and methods used to develop the indices. For the global-threat indices, we collected annual data and followed a consistent methodology for each of them. These indices are ranging from 0 (poor habitat quality) to 1 (good habitat quality) and are built on a regular 5 km grid covering the entire GBR Marine Park. They were each developed with the aim of reflecting the loss of coral cover caused by the threat.

An additional index has also been developed to provide an indication of the diffusion of land-based pollutants in the ocean. However, given the type of data collected for this index, the methodology used is quite different. Nevertheless, it provides valuable information on the location of river plumes and the amount of pollutants released by rivers.

All these indices can then be combined to obtain a global habitat quality index. We use the coral cover data to calibrate this global index. Indeed, the contribution of each threat is not precisely known and will therefore be deduced from the coral cover data.

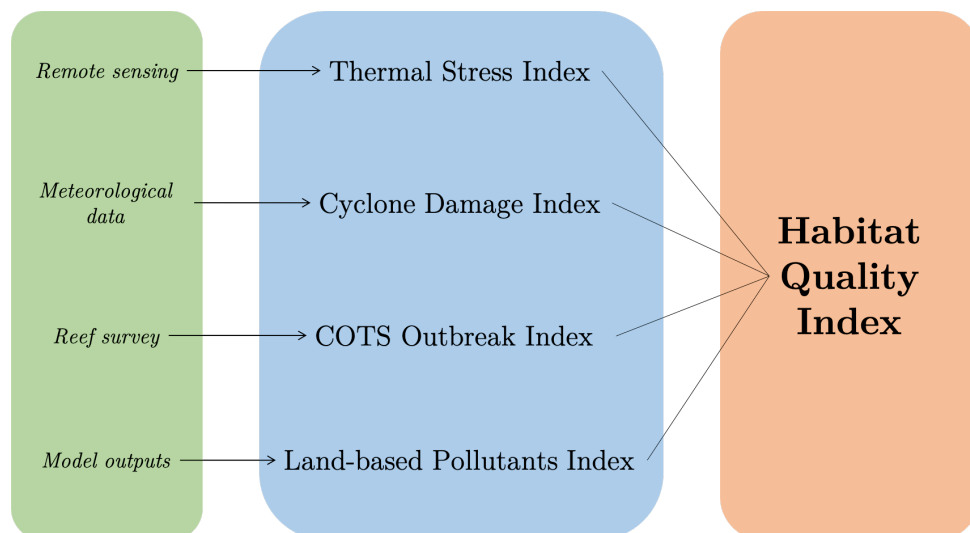


Figure 18: Steps of the methodology followed in this thesis: in green, the material used, in blue the indexes developed and in red, the global index.

## 2.1 Global-threat indices

### 2.1.1 Thermal stress

As shown in section 1.5.1, corals are very sensitive to sea temperatures anomalies. There is a clear correlation between sea temperature and occurrence of mass coral bleaching. In this section, we will explain the methodology used to construct the Thermal Stress Index (TSI), an index that provides an indication of the impact of bleaching on the health of any reef in the GBR.

If the sea temperature is 1 °C higher than the highest temperature expected in summer, corals can bleach (Glynn & D’Croze, 1990). This is called the “bleaching threshold”. To monitor and manage bleaching risks in areas as large as the GBR, satellite data are very useful. On board of some satellites is the *Advanced Very High Resolution Radiometer* (AVHRR), a sensor that allow to monitor sea surface temperature (SST) using radiation from the ocean surface. All data provided by the Coral Reef Watch (CRW) program is based on the SST. Among all of the products provided, the most advanced for monitoring coral bleaching is degree heating week (DHW). This product allows an easy identification of areas around the world where reefs are threatened by coral bleaching. Indeed, the DHW was designed to take into account how far the temperature exceeded the bleaching threshold but also how long it remained above it. According to CRW website, «the DHW shows how much heat stress has accumulated in an area over the past 12 weeks (3 months)»(Coral Reef Watch, 2019).

For the construction of this index, we have chosen to work with annual composite products. These products were provided using daily satellite data with a spatial resolution of 5 km. We collected annual maximum DHW for each year between 1985 and 2018 (NOAA Coral Reef Watch, 2019). We projected then all the data onto a regular 5 km grid over the entire GBR Marine Park. As we will work with other indices, this grid is very precisely located in space and used for the construction of each index in this work. This will allow to easily overlap all the indices.

Rather than using the DHW directly, we decided to go a step further and work with the probability of bleaching instead. Based on CRW research, when DHW exceeds 4°C-weeks, the most sensitive coral species can be expected to bleach. When it reaches 8°C-weeks or higher, mass bleaching events and mortality are expected. Table 3 illustrates the different levels of stress and their interpretations as defined by NOAA (Coral Reef Watch, 2019).

| Status        | Interpretation                                    | Definition                                 |
|---------------|---------------------------------------------------|--------------------------------------------|
| No Stress     | No heat stress                                    | DHW = 0<br>(SST below bleaching threshold) |
| Watch         | Low-level heat stress                             | DHW = 0<br>(SST below bleaching threshold) |
| Warning       | Heat stress accumulating                          | $0 < \text{DHW} < 4$                       |
| Alert Level 1 | Coral bleaching expected                          | $4 \leq \text{DHW} < 8$                    |
| Alert Level 2 | Widespread coral bleaching and mortality expected | $8 \leq \text{DHW}$                        |

Table 3: NOAA Coral Reef Watch has set up a bleaching alert system based on DHW. *Credit: NOAA CRW.*

Kayanne (2016) validates that DHW is efficient as an indicator of coral bleaching. He showed that «the recorded years of the bleaching events matched well with DHW values  $> 8$  °C-weeks ». According to him, a logistic regression can be used to determine the relationship between coral bleaching and DHW.

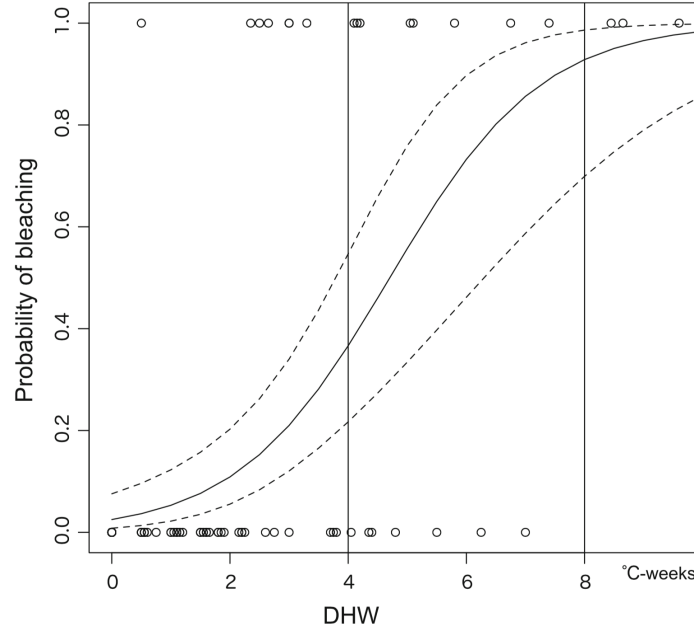


Figure 19: Logistic regression of probability of bleaching against NOAA CRW DHW from 2001 to 2015. 1 bleaching was reported; 0 bleaching was not reported. Dashed lines indicate 95% confidential intervals. *Credit: Kayanne (2016).*

On Fig. 19, we can observe that the probability of bleaching is  $> 0.35$  at 4 °C-weeks and  $> 0.9$  at 8 °C-weeks. These observations are consistent with the information in Table 3. The following equation is used to convert DHW to a probability of bleaching (Kayanne, 2016) :

$$p_b = \frac{1}{1 + a * b^{DHW}} \quad (1)$$

where :

$p_b$  = Probability of bleaching

$a = 49$

$b = 0.44$

The idea of the index is to reflect coral reefs health. Therefore, knowing the probability that reefs will be affected by a bleaching event is not sufficient, it is also essential to determine the probability of mortality in this case. This one is complex to establish because it varies according to many parameters. Muir Paul R. et al. (2017) analyzed the bleaching responses of 153 coral species. They showed that depth, shading and coral species had a significant effect on the susceptibility to be damaged by a bleaching event. There is a strong decline in bleaching damage with depth and some coral taxa show significant resilience. According to Wilkinson (2004), more than 90% of corals are killed

during severe bleaching events. It is this value that we will use as the probability of mortality in this work. However, we are aware that this value remains uncertain.

In order to calculate the thermal stress index, we use the following relation :

$$TSI(t_n) = \prod_{i=1985}^n \left( 1 - p_m * p_b(t_i) * e^{-\frac{t_n - t_i}{\tau}} \right) \quad (2)$$

where :

$TSI(t_n)$  is the Thermal Stress Index for year  $t_n$ ,

$p_m$  is the probability of mortality in case of bleaching (*set to 0.9*),

$p_b(t_i)$  is the probability of bleaching of year  $t_i$ ,

$\tau$  is the recovery characteristic time [yr] (*set to 4*),

$t_n$  is the year of the index [yr],

$t_i$  is the year of occurrence [yr].

Eq. (2) allows us to take into account the past climatic conditions for a certain location. For instance, if we want to know how much thermal stress affects a given reef in 2018, it is useful to know the effect of bleaching in 2018 but also for previous years. Indeed, it would not be relevant to consider that reef health depends only on current conditions. However, the reefs recover over time. In other words, the impact of a bleaching event decreases with time. The decreasing exponential of the equation reflects this last point. The recovery characteristic time is set to 4 years. This means that after a period of 10 years, the reef will have recovered nearly 90% or that a bleaching event that took place 10 years ago has only a 10% impact on the current health of the reef <sup>1</sup>.

As the TSI is calculated on the basis of the probability of bleaching (itself multiplied by a probability of mortality in case of bleaching), the index is expected to be between 0 and 1. If the value is low (close to 0) this means that the reef has been affected by many bleaching episodes over time and is therefore in poor condition. On the other hand, a reef with a high value means that it has been relatively spared by bleaching.

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<sup>1</sup>In other words, after 10 years, the remaining fraction of dead corals on a reef is  $e^{(-10/4)} = 10\%$  of what it was just after the bleaching.

### 2.1.2 Cyclone damage

Tropical cyclone (TC) are one of the main natural threats on coral reefs. As we have seen in section 1.5.2, they damage reef habitat quality in various ways. Between 1985 and 2012, a loss of 50.7% of initial coral cover was observed in GBR. TCs are the first to be responsible for this estimated loss. Indeed, they represent 48% of the damage on coral reefs, which is more than coral predation by COTS (42%) or coral bleaching (10%) (De'ath et al., 2012).

For the construction of the Cyclone Damage Index (CDI), we focus on the 47 TCs that have crossed the GBR Marine Park generating gale force winds ( $\geq 17m/s$ ) between 1985 and 2017. In order to be able to determine which reefs and to what extent they are affected by cyclones, we need a certain amount of information for each cyclone. First of all, it is important to know the year in which the cyclone crossed the GBR Marine Park. This enables us to know the attenuation of its impact over time. Indeed, over the years, corals recover and it is therefore expected that the damage from an old cyclone will be reduced over time. Then, it is necessary to know the area where reefs are damaged by cyclones. And finally, we need to know the destructive power of each cyclone.

Puotinen et al. (2016) provides valuable data on the 46 TC's that tracked near the Great Barrier Reef between 1985 and 2015. Among this data we find information on :

- *Intensity* : maximum surface wind speeds in m/s
- *Circulation size* : mean radius from the eye of the cyclone to the outer edge of gale force winds
- *Persistence* : total hours of gale force or higher winds within the GBR Marine Park

For Tropical Cyclone Debbie, the authors do not provide any information because it took place in 2017, one year after the study. However, due to the extent of the damage caused by this severe cyclone, an extensive technical report was published by the Australian Bureau of Meteorology (BoM, 2018). With this report, it is possible to estimate the missing data. All data collected for the 47 cyclones are presented in Appendix A.

Thanks to all these data, Beeden et al. (2015) have developed a “Structural Damage Risk” index. This index corresponds to an indicator of the likelihood that the storm causes structural damage to reefs. It takes into account 3 keys factors: the intensity, the circulation size and the duration of extreme conditions near reefs (‘persistence’). For each TC, the “Structural Damage Risk” index (SDR) is calculated with the following relation :

$$SDR = \left( \frac{Intensity}{Intensity\ max} \times \frac{Circulation\ size}{Circulation\ size\ max} \times \frac{Persistence}{Persistence\ max} \right) \times 100, \quad (3)$$

where each factor is scaled to maximum recorded value (*Intensity max* – 68 m/s; *Circulation size max* – 495 km; *Persistence max* – 87 hours).



Fabricius et al. (2008) estimated the impact on reef of tropical cyclone Ingrid, which crossed the GBR in 2005. For this study, 82 sites on 32 reefs along the cyclone track were surveyed. These numerous observations have shown how damage is distributed along the wind gradient. This study showed that the *maximum wind speed* is the best predictor of reef damage. The maximum intensity is therefore the most suitable for assessing damage to coral reefs than the SDR index.

As we know the maximum intensity (maximum wind speeds) of each cyclone, this information must be interpreted as a real impact on corals. Wind speeds can be converted into 5 categories of Australian cyclonic intensity (Table 4). These categories are based on maximum 10-min sustained wind speeds (in m/s). For the 5 categories of cyclones, Fabricius et al. (2008) provide an indication of the damage to corals. This indication is given in the form of the percentage of coral lost as shown in Appendix B.

| Category | Wind speed range | Coral Loss |
|----------|------------------|------------|
| 1        | 17 - 24.5 m/s    | 5 %        |
| 2        | 24.6 - 32.5 m/s  | 20 %       |
| 3        | 32.6 - 44.2 m/s  | 50 %       |
| 4        | 44.3 - 55.3 m/s  | 70 %       |
| 5        | >55.4 m/s        | 95 %       |

Table 4: Maximum hourly wind speeds are converted to categories of Australian cyclonic intensity, based on maximum 10-min sustained wind speeds (in m/s). *Credit: Fabricius et al. (2008).*

Table 5 summarizes Structural Damage Risk (SDR), maximum intensity (maximum surface wind speeds in m/s) and Australian cyclonic category (1-5) for each of the 47 cyclones of this study.

| Name     | SDR  | Intensity | Cat | Name    | SDR  | Intensity | Cat | Name    | SDR  | Intensity | Cat |
|----------|------|-----------|-----|---------|------|-----------|-----|---------|------|-----------|-----|
| Larry    | 3,7  | 68        | 5   | Celeste | 3,4  | 40        | 3   | Nathan  | 3,3  | 23        | 1   |
| Hamish   | 14,2 | 62        | 5   | Rona    | 5,4  | 39        | 3   | Abigail | 0,9  | 23        | 1   |
| Yasi     | 11,4 | 61        | 5   | Charlie | 7,0  | 35        | 3   | Ellie   | 1,8  | 23        | 1   |
| Ita      | 15,5 | 59        | 5   | Steve   | 1,3  | 33        | 3   | Mark    | 0,8  | 22        | 1   |
| Marcia   | 5,8  | 58        | 5   | Fran    | 24,3 | 32        | 2   | Justin  | 16,5 | 22        | 1   |
| Ingrid   | 4,9  | 54        | 4   | Olga    | 2,8  | 32        | 2   | Tasha   | 0,7  | 22        | 1   |
| Debbie   | 38,7 | 54        | 4   | Zane    | 0,6  | 31        | 2   | Ita     | 0,7  | 21        | 1   |
| Aivu     | 11,9 | 52        | 4   | Tanya   | 3,4  | 30        | 2   | Nina    | 8,3  | 20        | 1   |
| Joy      | 31,1 | 52        | 4   | Ethel   | 0,8  | 30        | 2   | Fritz   | 0,5  | 20        | 1   |
| Oliver   | 19,5 | 46        | 4   | Pierre  | 1,1  | 29        | 2   | Edna    | 0,2  | 20        | 1   |
| Nathan   | 19,0 | 46        | 4   | Guba    | 1,2  | 29        | 2   | Manu    | 1,5  | 19        | 1   |
| Winifred | 14,7 | 45        | 4   | Anthony | 1,7  | 29        | 2   | Kelvin  | 0,7  | 18        | 1   |
| Ului     | 2,2  | 43        | 3   | Tessi   | 2,1  | 28        | 2   | Jim     | 0,4  | 18        | 1   |
| Monica   | 7,5  | 42        | 3   | Dylan   | 17,0 | 28        | 2   | Oswald  | 12,5 | 18        | 1   |
| Ivor     | 10,6 | 41        | 3   | Tim     | 5,1  | 26        | 2   | Meena   | 0,4  | 17        | 1   |
| Rewa     | 12,3 | 41        | 3   | Kate    | 1,0  | 24        | 1   |         |      |           |     |

Table 5: Structural Damage Risk (SDR), maximum intensity (maximum surface wind speeds in m/s) and Australian cyclonic category (1-5) for each of the 47 cyclones of the study.

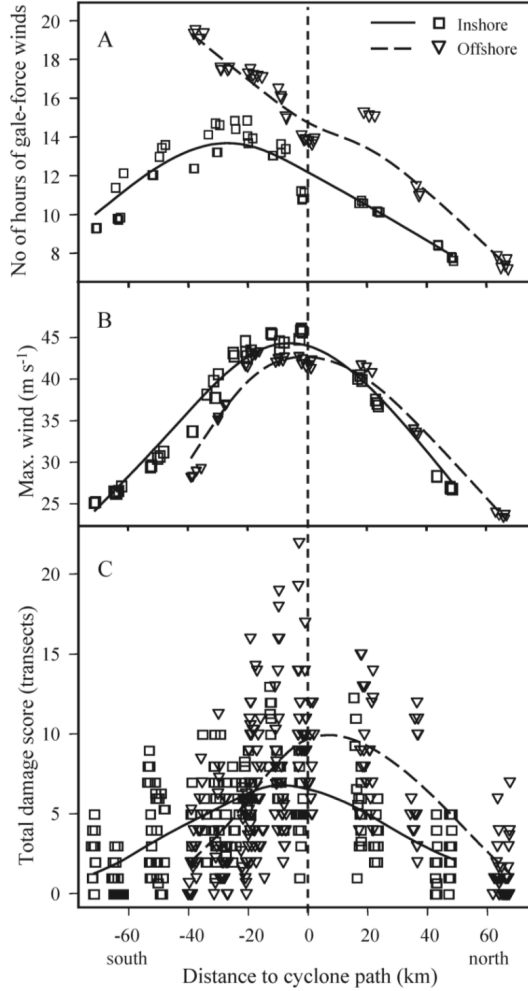


Figure 20: (A) Spatial gradients in the number of hours of gale force wind. (B) 10-min averaged maximum wind speed at each site plotted against distance to the cyclone path. (C) Total damage to reefs as a function of distance to the cyclone path. *Credit: Fabricius et al. (2008).*

both offshore and inshore reefs, damage decreases with increasing distance from the path. Although there are significant differences between inshore and offshore reefs, it can be seen that damage decreases with distance following a linear trend (Fabricius et al., 2008).

Because of the difficulties to find the wind speed profile of each of the 47 cyclones required to construct our index, we found another alternative. We created a buffer zone around the path of each cyclone. This buffer zone will have as a distance the circulation size, which means that it corresponds to the zone where wind speeds are higher or equal to 17 m/s (gale force wind). This buffer will then be divided into 3 areas as shown in Fig. 21. Reefs in the area closest to the cyclone path (red zone) will be damaged as if they were impacted by the maximum wind speed of the cyclone. In the second zone (orange zone), reefs will be impacted by a wind equivalent to 2/3 of the maximum intensity of the cyclone. Finally, in the area farthest from the cyclone path (green zone), only 1/3 of the maximum wind speed will damage the reefs.

Once we know the destructive potential of each cyclone, it is important to know which reefs are located within the area of influence of each cyclone. To get this information, the first thing to know is the path of each cyclone. We collected cyclone tracks on the Australian Bureau of Meteorology website (BoM, 2018). Circulation sizes of cyclone are already known since they were previously used to calculate the SDR index. They correspond to the distance up to which gale force winds can be found. However, considering that the damage to coral reefs is homogeneous throughout the area of influence of the cyclone is not correct. Indeed, the more the wind speed increases, the more kinetic energy is important and therefore the more extensive the damage will be. All tropical cyclones have typical wind profile. At the centre of a cyclone's eye, the wind speed is zero but it increases dramatically in the eyewall. Then, the wind speed gradually decreases further away from the cyclone (Environment and Climate Change Canada, 2013).

The variation in wind speed around the cyclone path is illustrated in Fig. 20b. As expected, we can see that the speed decreases as we move away from the cyclone path. Fig. 20c shows the damage caused by cyclone Ingrid to the surveyed reefs. To assess the damage, 7 categories have been defined (e.g. framework removed, coral breakage,...) rated between 0 and 5. The "total damage score" (y-axis of the last graph) is the sum of the scores of the 7 categories. For

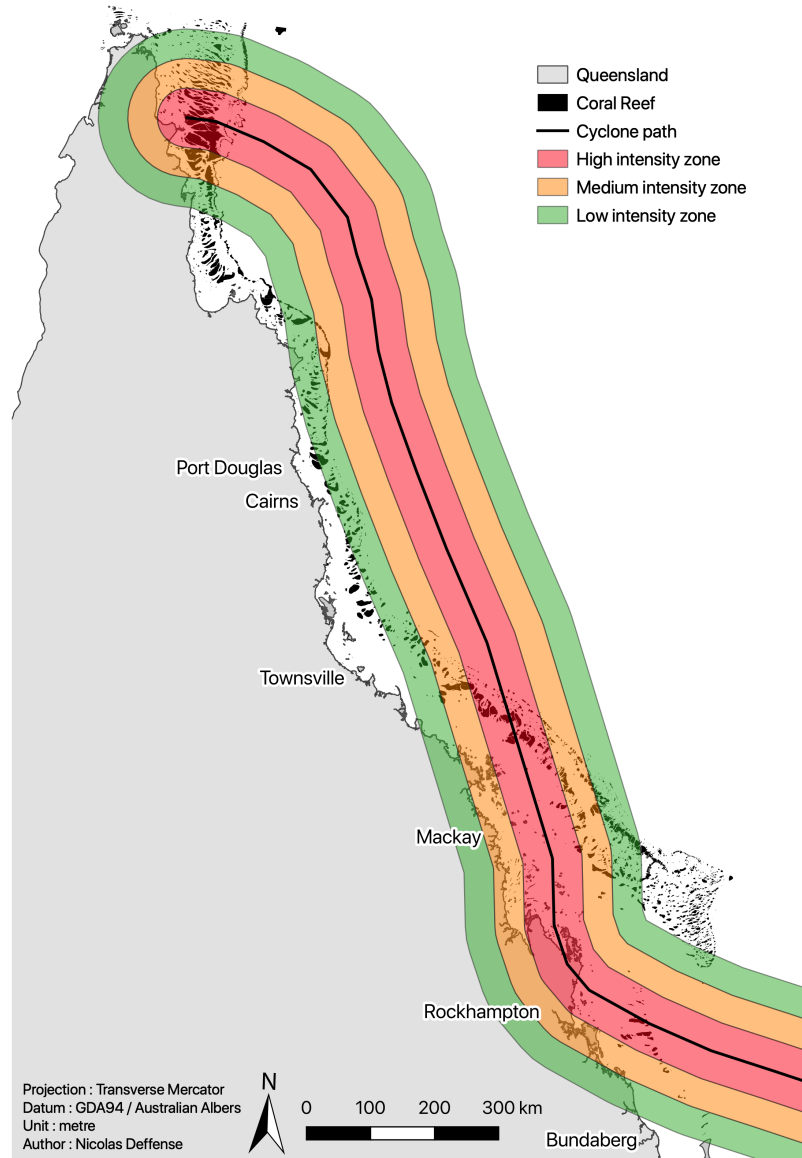


Figure 21: Buffer zones for Cyclone Pierre. Red zone near the cyclone path is the high intensity zone. Orange zone is an area where the intensity is reduced by  $1/3$ , it is the medium intensity zone. In the green zone, the intensity is reduced by  $2/3$  compared to the red zone. This zone is called the low intensity zone.

For example, Cyclone Ita has a maximum intensity of 59 m/s and is therefore defined as category 5 cyclone (Table 5). Thanks to the construction of the 3 buffer zones around each cyclone, we can have a more detailed analysis of the extent of damage to corals. Indeed, it would not make sense to assume that a reef located very far away from the track of a category 5 cyclone has its coral cover reduced by 95% (Table 4). For this reef we first calculate the reduced wind speed as explained above. Then we calculate the category of the cyclone able to generate such a wind. Finally, we can relate the cyclonic category to the loss of coral cover using the Table 4.

Once we have calculated the damage that each cyclone causes to the reefs (i.e. loss in coral cover), we must take into account the recovery of corals over time. The following relation allows to quantify the damage caused by each cyclone depending on the year of occurrence of the cyclone :

$$CDI(t_n) = \prod_{i=1}^n \left( 1 - l_i * e^{-\frac{t_n - t_i}{\tau}} \right) \quad (4)$$

where :

$CDI(t_n)$  is the Cyclone Damage Index for year  $t_n$ ,

$l_i$  is the coral cover loss caused by cyclone 'i',

$\tau$  is the recovery characteristic time [yr] (*set to 4*),

$t_n$  is the year of the index [yr],

$t_i$  is the year of occurrence of cyclone 'i' [yr],

$n$  is the number of cyclone occurring between 1985 and  $t_n$ .

For example, if a cyclone crossed the GBR Marine Park in 2008, its effect on corals is expected to be significantly reduced 10 years later. Thanks to the exponential term in the equation, this cyclone will have a 90% lower impact 10 years after its passage. To obtain an global index for a given year T, we calculate the product of the impact of each cyclone that occurred before year T.

### 2.1.3 Crown-of-thorns starfish outbreaks

Crown-of-thorns starfish (COTS) is the main predator of corals in the GBR. COTS outbreaks can drastically reduce living coral cover on healthy reefs within a few weeks (Osborne et al., 2011). Collecting information on the location and the severity of outbreaks is crucial to protect coral reefs. This section explains how the COTS Outbreak Index (COI) is developed.

Data used to build this index is sourced from Australian Institute of Marine Science (AIMS) as part of the Long-Term Monitoring Program (AIMS, 2015). One of the main tasks of this program is to monitor COTS in the GBR. To achieve this objective, 181 reefs in 11 sectors of the GBR are surveyed at least every 3 years. Among the monitored reefs, 64 reefs considered as ‘key’ reefs are annually surveyed. Observations were initiated in January 1982 and are still ongoing.

The procedure chosen for broadscale surveys of COTS is the manta tow technique. This technique enables to describe large areas of reefs as well as to give indications on potential changes in abundance and distribution of reef organisms. Developed in 1969 by Chesher, this technique was first intended to evaluate COTS densities in Micronesia and since the 1970’s, it has been widely used on the GBR. The technique involves a snorkel diver holding on to a ‘manta board’ towed behind a small boat as the boat circumnavigates a reef (Fig. 22a). Every two minutes the boat stops and the diver records results on a data sheet, in this case, the number of COTS present on the reef (Fig. 22b). Data from all reefs and for each year are then collected in a database. This technique has the advantage of enabling the survey of large areas quickly and with minimal equipment (Bass & Miller, 2003).

As COTS are solitary animals, the manta tow technique does not allow an accurate estimate of the total number of COTS present on a specific reef. It is estimated that there are about 10 times more COTS than observed during manta tow surveys. A density of at least 1.0 COTS per tow is considered sufficient to trigger an “**active outbreak**”. At this density, COTS are highly likely to lead to a clear decline in corals. When the density is between 0.22 and 1.0 COTS per tow, we are in the situation of an “**incipient outbreak**” (Lawrey, 2014).

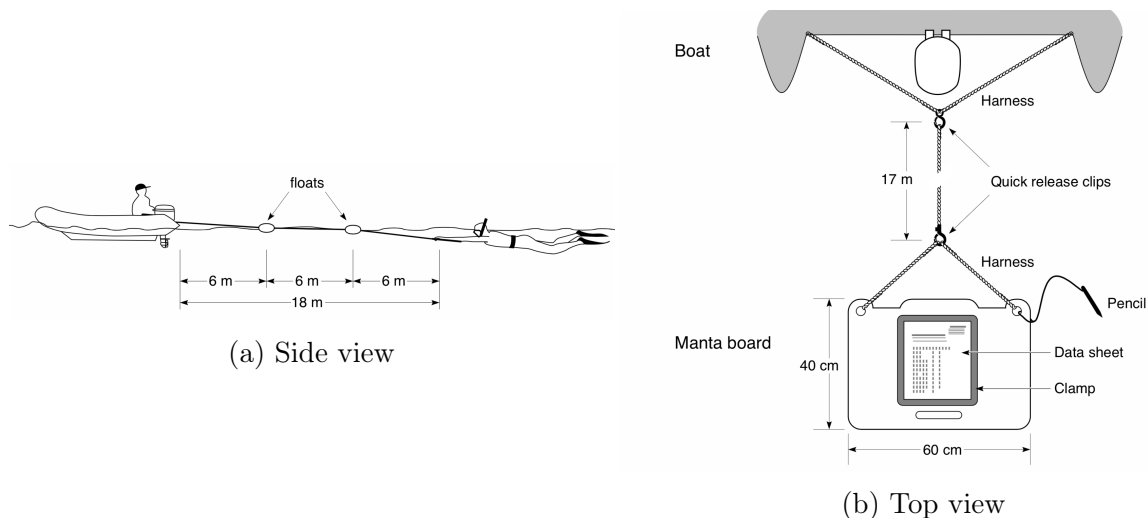
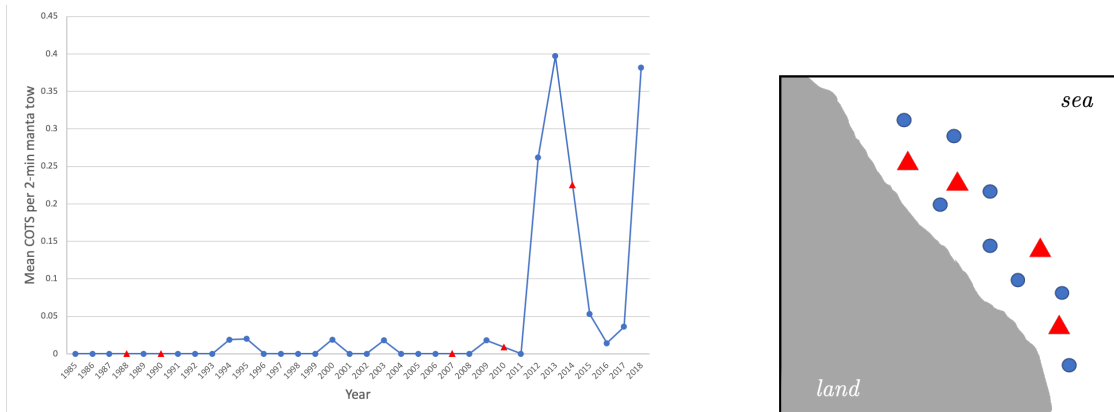


Figure 22: Manta tow technique. *Credit: Bass & Miller (2003).*

The first step in the construction of this index is to find the COTS density for each GBR reef and for each year. For this purpose, we perform a spatial interpolation for each year using the data provided by AIMS. The data are interpolated using the “Inverse Distance Weight” (IDW) function. The IDW is based on the inverse of the distance raised to a mathematical power. With the power parameter, it is possible to control the influence of known points on the interpolated values according to their distance. This is a positive and real number with a default value of 2, which we have maintained for this work. We use a 100 km search radius (as used by AIMS), which means that a surveyed reef will impact the reefs around it within a 100 km radius.

To perform this type of interpolation it is important to have enough and well distributed data. During some years, a very large number of reefs have been monitored, for example, 285 reefs were surveyed in 1985-86. However, for other years, only about 50 reefs have been monitored throughout the GBR. This represents a significant lack of accuracy in performing IDW interpolation over the entire GBR. The most recent years, and therefore the most important years in the calculation of our index, are the most affected by this lack of data.

To overcome this problem, we use temporal interpolation to add data before performing IDW interpolation. Indeed, we observe that some reefs have been monitored a significant number of times over the past 34 years (1985 - 2018). For these reefs, we have a clear understanding of the evolution of COTS density over the years. This allows us to estimate the COTS density for years when the information is missing. This is a temporal interpolation where missing values from certain years are interpolated using data from the years in which the measurement was done (Fig. 23a). To obtain the most correct interpolation possible we will only work with reefs that have been monitored at least *15 times since 1985* and have been monitored at least *once since 2016*. This ensures that these reefs are surveyed about once every 2 years and that they have been recently surveyed. In total, there are 52 reefs that meet these criteria which we will call the ‘*super-monitored*’ reefs.



(a) Temporal interpolation for COTS density - the blue dots represent known data while the red triangles represent interpolated values of MEAN COTS per tow for years when monitoring did not take place on the reef. *Credit: (AIMS, 2015).*

(b) The blue dots represent the surveyed reefs in a given year. Red triangles are ‘*super-monitored*’ reefs whose value has been interpolated.

Figure 23: COTS temporal interpolation

Once the temporal interpolation is done, we can spatially interpolate the known data for each year. Firstly, we use the reefs monitored during the year of interest. Secondly, we complement with ‘*super-monitored*’ reefs to have more and better distributed data (Fig. 23b).

The second step is to establish a link between the COTS density and the damage caused to corals. A fine-scale study project, led by RCINT (*Reefcare International Pty Ltd*), during the third COTS outbreak event in the 1990’s, determined the actual mortality rates of hard corals on outbreaking reefs (Engelhardt et al., 2001). Reefs were monitored each year, with COTS abundance and hard coral cover assessed simultaneously using intensively sampled benthic  $50 \times 5$  m transects. The estimated rate of “natural” loss of hard coral cover (LHCC) in the presence of COTS outbreaks of varying intensity, but in the absence of any COTS control action, is shown in Fig. 24. It can be seen that COTS densities between 1.0 and 5.0 COTS per  $250 \text{ m}^2$  would typically consume between 25 and 70% of the coral population available over a 12-month period.

Keesing (1990) suggested that a density of 10 to 15 adult COTS per hectare (i.e. 0.25 to 0.375 per  $250 \text{ m}^2$ ) could be maintained in areas with 20 to 50% living coral cover. In his study, Engelhardt et al. (2001) used a higher threshold of 0.75 individuals per  $250 \text{ m}^2$  which is more conservative and takes into account some additional variables, such as possibly higher coral cover and reduced feeding rates depending on the season. This means that if the COTS density is less than or equal to 0.75 individuals per  $250 \text{ m}^2$ , we assume that there is no loss of coral cover.

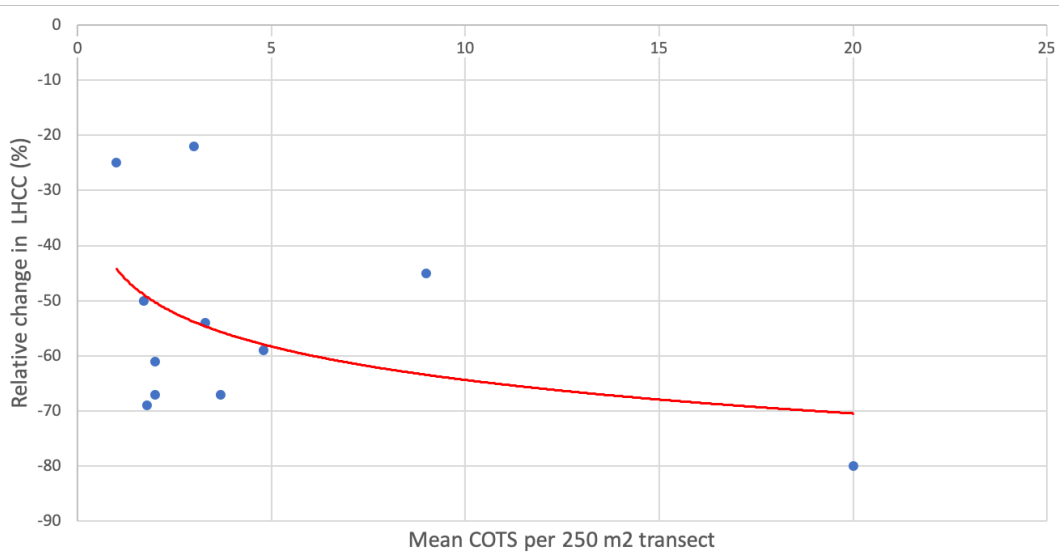


Figure 24: Relationship between COTS abundance and the loss of hard coral cover (LHCC) in the absence of active COTS controls over a 12-months period. *Credit: Engelhardt (2018).*

As mentioned above, data provided by AIMS give the density of COTS in ‘mean COTS per 2-min manta tow’. However, converting this COTS density into the number of COTS *per unit area* is possible because, according to Hughes et al. (2014), 15 starfish per hectare is equivalent to 0.22 starfish per 2-min manta tow. This means that 1 COTS per tow is equivalent to 68 COTS per hectare. On the basis of the graph in Fig. 24, we have produced another graph that is better adapted to our data and what we want to do with it in the context of this work (Fig. 25).



The following relation is used to determine the loss of coral cover given the density of COTS per manta tow :

$$LHCC = \begin{cases} 8.75 * \ln d + 49, & \text{if } d \geq 0.44 \\ 0 & \text{otherwise} \end{cases} \quad (5)$$

where  $LHCC$  is the Loss of Hard Coral Cover (%) and  $d$  is the mean COTS per 2-min manta tow.

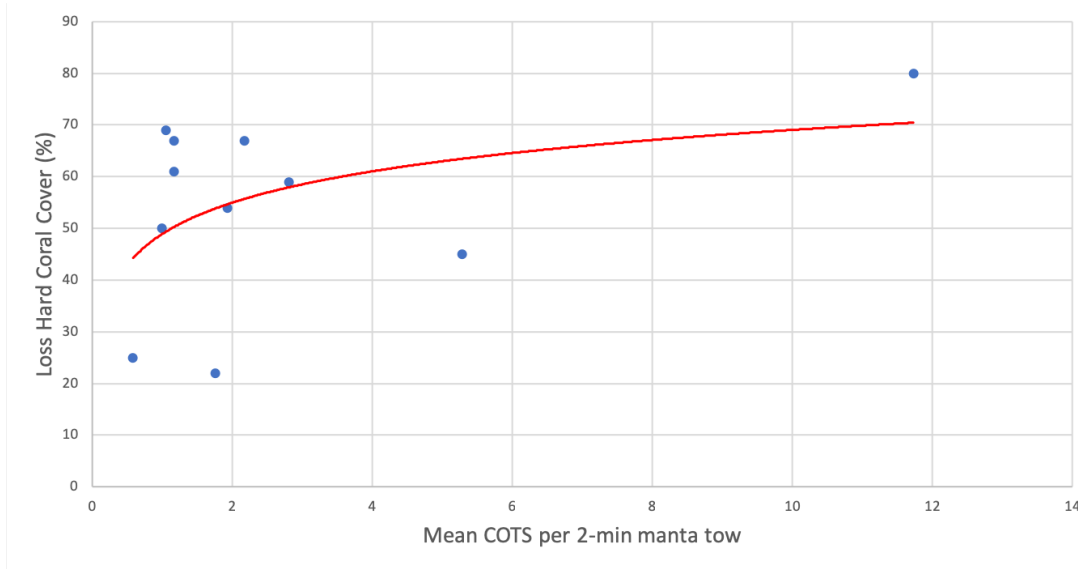


Figure 25: Relationship between COTS density (per 2-min manta tow) and the loss of hard coral cover (LHCC) in the absence of active COTS controls over a 12-months period. *Graph adapted from Engelhardt (2018).*

We now combine data from each year. This allows us to take into account the reefs recovery. In terms of coral cover, reefs can take 12 to 15 years to recover from a COTS outbreak (Moran, 1986). This is why we have set the recovery characteristic time to 4 years so that after a 15-year period the impact of an outbreak is almost completely zero (decrease of 98%). The COTS Outbreak index then reads :

$$COI(t_n) = \prod_{i=1985}^n \left( 1 - LHCC(t_i) * e^{-\frac{t_n - t_i}{\tau}} \right) \quad (6)$$

where :

- $COI(t_n)$  is the COTS Outbreak Index for year  $t_n$ ,
- $LHCC(t_i)$  is the Loss of Hard Coral Cover during year  $i$  (%),
- $\tau$  is the recovery characteristic time [yr] (*set to 4*),
- $t_n$  is the year of the index [yr],
- $t_i$  is the year of occurrence [yr].

## 2.2 Local-threat indices

The 3 indices previously mentioned represent the main global threats to the GBR: bleaching, tropical cyclones and COTS outbreaks. For these threats, many different data sources (remote sensing, meteorological data, reef monitoring,...) are available. This allows a good understanding of the damage areas. Most of these data have been recorded annually since 1985 for GBR, which gives a good overview of the evolution of damage to coral reefs. In addition, numerous studies have estimated the loss of coral cover associated with each of these threats.

Since the objective of this thesis is to obtain an index on the global habitat quality, we have focused on the main threats. However, we decided to investigate a fourth index taking into account the runoff of land-based pollutants into the ocean. As discussed in section 1.5.4, Queensland releases a significant amount of land-based pollutants. Agricultural activities discharge these pollutants into the sea through the river network. The impact of the near-shore water quality can be important and cause significant damage to corals.

### 2.2.1 Land-based pollutants

The first step in the construction of the Land-based Pollutants Index (LPI) is to find out the location of the rivers, and more particularly their mouths. In addition to this, it is also important to know to which catchments each river belongs. This makes it possible to estimate the amount of pollutants that can be expected to be released at each river mouth. Data on catchment boundaries and major rivers were collected through the Queensland Spatial Catalogue (2018). A table showing the 39 major rivers, their respective catchment and the location of their mouths is provided in Appendix G.

Once we know the location of the mouths of each river, the second step is to model the river's plume. The plume spreads, mixes and moves with winds and currents. A naive approach would be to model it by a circular gradient centred on the mouth of the river (Fig. 26.a). However, observation of the "MECCA 3-dimensional hydrodynamic model" outputs shows that plumes tend to follow the coast rather than go far into the sea (King et al., 2002). This model demonstrates that the main driving forces on the plume are the volume of river discharge, the local wind forcing and the Coriolis force. We therefore observe an ellipsoidal pattern of the plumes (Fig. 26.b). Taking into account the orientation of the coast, Fig. 26.c is obtained.

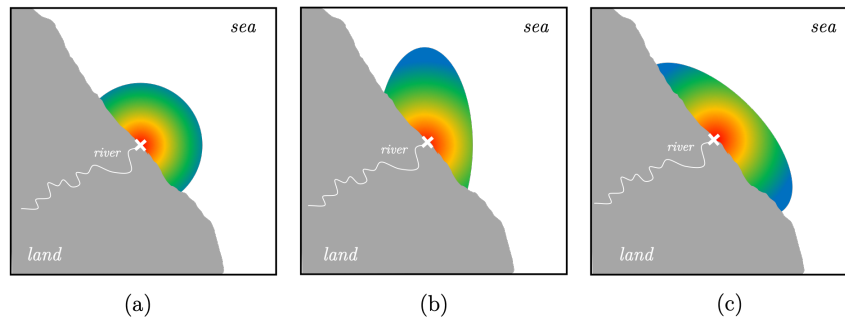


Figure 26: Increasing complexity of the land-based pollutant diffusion model : from circular diffusion (a) to ellipsoidal diffusion (b) taking into account the orientation of the coast (c).

The diffusion of pollutants into the sea from the mouth of a river can be modelled using an exponentially decreasing concentration  $C(\mathbf{x}, \mathbf{y}) = e^{-d/d^*}$ , where  $d$  is a distance (to be defined later) to the river mouth and  $d^*$  is a characteristic distance of decay. The concentration of pollutants  $C(\mathbf{x}, \mathbf{y})$  decreases exponentially with distance  $d$ . In order to fit our model as much as possible to reality we will adapt the way of calculating the distance from the river mouth. The following equations show 3 ways to calculate the distance, to move from a simple circular diffusion model to a complex ellipsoidal diffusion model. We will use equation 7c because it is the best fit with the river plumes in the GBR.

$$d = \sqrt{\mathbf{X}^2 + \mathbf{Y}^2} \quad (7a)$$

$$= \sqrt{\alpha \mathbf{X}^2 + \beta \mathbf{Y}^2} \quad (7b)$$

$$= \sqrt{\alpha(\cos(\theta)\mathbf{X} - \sin(\theta)\mathbf{Y})^2 + \beta(\sin(\theta)\mathbf{X} + \cos(\theta)\mathbf{Y})^2} \quad (7c)$$

where :

- $d$  = distance from the river mouth [m]
- $\mathbf{X}$  =  $\mathbf{x} - \mathbf{x}_0$
- $\mathbf{Y}$  =  $\mathbf{y} - \mathbf{y}_0$
- $\mathbf{x}_0, \mathbf{y}_0$  = coordinates of the river mouth
- $\alpha, \beta$  = ellipsoidal parameters (*set to 5 and 1 respectively*)
- $\theta$  = orientation of the coast [ $^\circ$ ]

After modelling each river plume, we must quantify the impact that each river has on the GBR ecosystem. To simplify things, we assume that for each catchment, there is a single large river that discharges all the land-based pollutants into the sea. This is not an unreasonable hypothesis because more than 70% (25 out of 35) of the catchments actually have a single end-of-catchment river. The classic pattern is a network of rivers draining the entire catchment area and ending up in the sea at a single outlet.

Chapter 2 of the *Scientific Consensus Statement* (Bartley et al., 2017b) gives an estimate of the end-of-catchment pollutant load of the 35 catchments along the GBR coast. These estimates are provided using the ‘‘Source Catchments model’’ (eWater, 2010), which applies algorithms that represent processes, such as erosion, using site-specific input data like soil type and run-off. It should be noted that the amount of pollutants generated is not necessarily equivalent to the amount of pollutants discharged into the sea. Indeed, many processes take place along the way. The results we use here are the pollutant load delivered to the sea. The pollutants modelled are fine and coarse sediments (TSS), particulate and dissolved nutrients (PP, PN, DIN) and five photosystem II herbicides (PSII). All the results that will be used in this thesis are summarized in Appendix E (Bartley et al., 2017b).

In order to obtain a more accurate modelling of land-based pollutants, each of the 3 main categories of pollutant will be assigned its own index.

$$SI(\mathbf{x}, \mathbf{y}) = \sum_{i=1}^n TSS_i \exp\left(\frac{-d}{d^*}\right) \quad (8a)$$

$$NI(\mathbf{x}, \mathbf{y}) = \sum_{i=1}^n (DIN_i + PN_i + PP_i) \exp\left(\frac{-d}{d^*}\right) \quad (8b)$$

$$PI(\mathbf{x}, \mathbf{y}) = \sum_{i=1}^n PSII_i \exp\left(\frac{-d}{d^*}\right) \quad (8c)$$

Equation 8a represents the Sediment Index (SI) taking into account the total suspended sediment (TSS) discharged by each river into the sea. Then, equation 8b illustrates the Nutrient Index (NI) that reflects the impact of the 3 major nutrients that impact the GBR ecosystem: dissolved inorganic nitrogen (DIN), particulate nitrogen (PN) and particulate phosphorus (PP). Lastly, equation 8c allows us to calculate the Pesticide Index (PI). This index considers the sum of the five prevalent PSII herbicides in GBR (ametryn, atrazine, diuron, hexazinone and tebuthiuron).

The parameter  $d^*$  present in the denominator of each equation is a factor determining the distance of influence of each river. It is set at 100 km and does not vary from one river to another. This means that when the distance to the coast ( $d$ ) reaches 100 km, the amount of pollutant decreases by about 63%. This value was approximated by analyzing the outputs of the “MECCA 3-dimensional hydrodynamic model” presented by King et al. (2002).

For the calculation of these indices, many hypothesis are made:

- Land-based pollutants spread in the sea in the same way. We do not take into account the fact that some elements such as DIN could spread better than others. We lack precise information on this subject and this will make the model too complex.
- The river plume is quite approximate because in reality it is highly variable both inter and intra-year. The ellipsoidal parameters  $\alpha$  and  $\beta$  were approximated based on river plume modelling results. We estimate them to be similar for each river in the GBR.

Lastly, we normalize each index between 0, a water highly contaminated with pollutants, and 1, a good quality water, low in pollutants.

$$Index(\mathbf{x}, \mathbf{y}) = 1 - \frac{[Index(\mathbf{x}) - \min(Index)]}{[\max(Index) - \min(Index)]} \quad (9)$$

In order to have a global idea of the impact of pollutants on the GBR Marine Park, we have combined the indices for the 3 main sources of pollutants. As we do not have a precise indication of the weighting of these 3 types of pollutants, we have decided to assign an equal weight to each index. The following relation is used to calculate the global index that we call Land-based Pollutants Index (LPI) :

$$LPI = \frac{1}{3} \times SI + \frac{1}{3} \times NI + \frac{1}{3} \times PI \quad (10)$$

## 2.3 Global Reef Habitat Quality Index

A global index of reef habitat quality (HQI) can now be calculated by combining all previous indices. It takes into account the four threats to the GBR in order to be as accurate as possible. This index ranges from 0 to 1, with a value of 1 meaning that habitat quality for reefs is the best, while a value of 0 means poor habitat quality.

For every reef  $i$ ,

$$\text{HQI}_i = \text{TSI}_i^\alpha \times \text{CDI}_i^\beta \times \text{COI}_i^\gamma \times \text{LPI}_i^\delta \quad (11)$$

with  $0 \leq \alpha, \beta, \gamma, \delta$

where :

HQI is the Habitat Quality Index,

TSI is the Thermal Stress Index,

CDI is the Cyclone Damage Index,

COI is the COTS Outbreak Index,

LPI is the Land-based Pollutants Index,

$\alpha, \beta, \gamma, \delta$  is the contribution of each threat to be optimized.

In order to calibrate the model, i.e. find the contributions of each threat, we use the coral cover (CC) data. Indeed, the percentage of living coral cover on a reef reflects the impact of all the threats it has experienced. Coral cover can be seen as an indicator of reef quality. The healthier the environment, the more corals cover the reefs. As a result, if the habitat quality index is high, it would be consistent to observe a high coral cover as well. Conversely, if the quality of the habitat is poor in a certain area, the coral cover should be low.

The Coral Cover data used is obtained from the AIMS database. In addition to recording COTS density on reefs using the manta tow technique, AIMS also provides data about the percentage cover of live coral (AIMS, 2015).

In order to know the optimal values of the model parameters, we will minimize<sup>2</sup> the following function :

$$\begin{aligned} & \text{minimize} \quad \frac{1}{n} \sum_{i=1}^n (\text{HQI}_i - \text{CC}_i)^2 \\ & \text{minimize}_{\alpha, \beta, \gamma} \quad \frac{1}{n} \sum_{i=1}^n (\text{TSI}_i^\alpha \times \text{CDI}_i^\beta \times \text{COI}_i^\gamma \times \text{LPI}_i^\delta - \text{CC}_i)^2 \\ & \text{subject to} \quad 0 \leq \alpha, \beta, \gamma, \delta \end{aligned}$$

Indeed, we look for parameters for which the difference between the habitat quality index and the coral cover is minimal. The results are presented in the following section.

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<sup>2</sup>The applied method is SLSQP using Sequential Least Squares Programming to minimize a function of several variables with any combination of bounds, equality and inequality constraints. More information on SciPy.org

### 3 Results

Great Barrier Reef Marine Park Authority (GBRMPA) have subdivided the GBR Marine Park into 4 management units. These management units are used to facilitate the results analysis. Statistics for each index are calculated according to these 4 zones. Fig. 27 shows the boundaries of the management units and the reefs they contain.

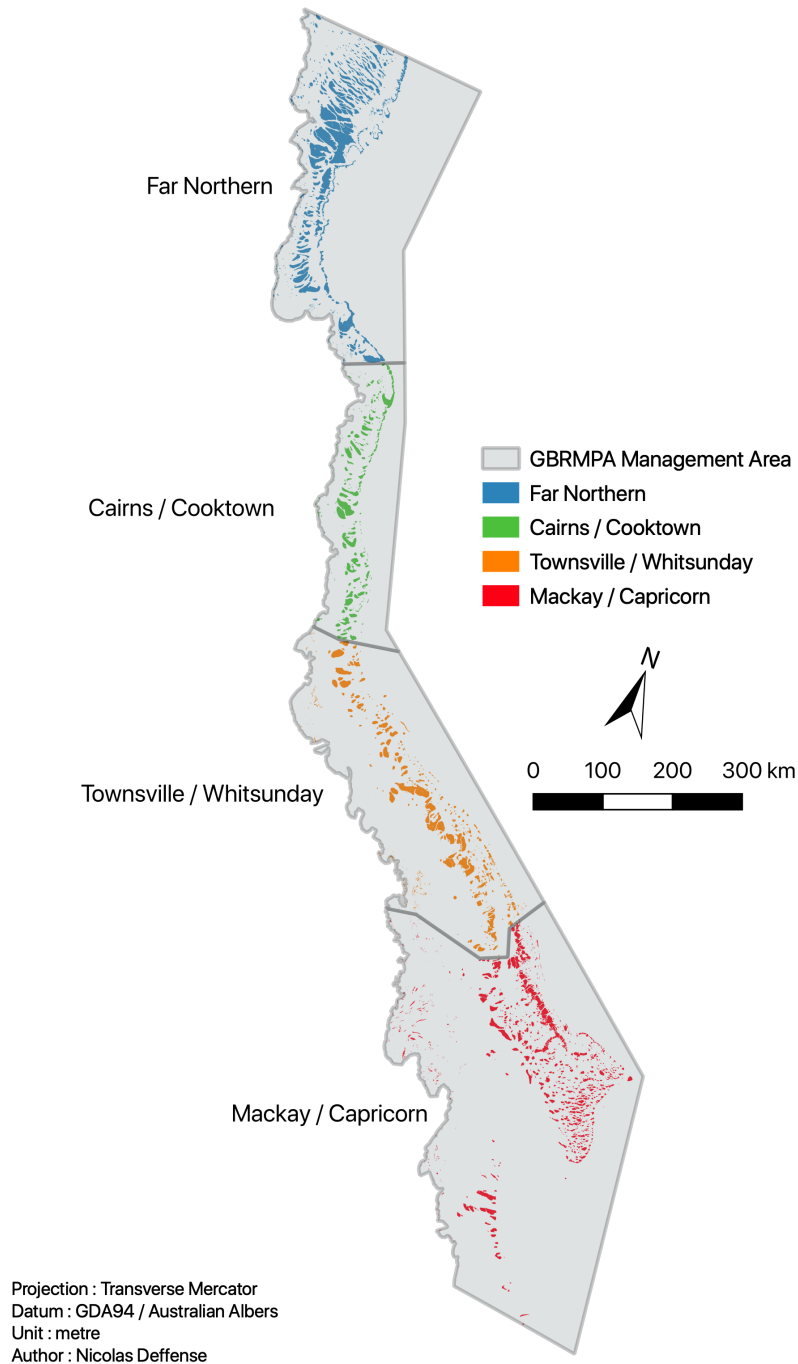


Figure 27: GBR Marine Park Management Units

### 3.1 Thermal Stress Index

Thermal Stress Index (TSI) is an indicator of the impact of sea temperature anomalies on corals. As described in the section 2.1.1, it was designed on the basis of the DHW which was then converted into a bleaching probability. Multiplying this bleaching probability by the probability of mortality of bleached corals gives an indication of habitat quality. When the index is low (close to 0), the risk of bleaching is very high and therefore corals suffer a high mortality rate leading to a significant loss of coral cover. On the other hand, if TSI is high (close to 1), the habitat is of high quality and does not suffer any bleaching damage. There is therefore no or very little loss of coral cover.

This index was developed for each year from 1985 and therefore makes it possible to monitor the trend in bleaching damage. In the framework of this thesis, we focus on the results of the last 4 years (2015 - 2018), as it is these years that provide a better understanding of the current state of reef health in the GBR Marine Park.

Fig. 28 shows TSI evolution from 2015 to 2018. The more reddish an area is, the more one expects to observe a high loss of coral cover due to bleaching. When values are high (blue-green areas), corals with a higher coral cover are expected to be observed. The main statistics for each of the 4 management units are presented in Appendix H and summarized in Fig. 28.

When we look at the maps in the Fig. 28, the first striking observation is the large area where TSI is very low. This area is mainly located in the northern part of the GBR in the Far Northern and Cairns/Cooktown management areas. This degradation of the reefs begins in 2016. During this year, there was an overall decrease in TSI of 26% compared to 2015. This decrease is most pronounced in the Far Northern region where the mean TSI falls by 84% compared to the previous year.

We can observe a second decrease in the mean TSI between 2016 and 2017. While corals should normally recover from bleaching, during this period they suffer more damage. The mean TSI on the entire GBR falls to 0.39 in 2017 (-34% of 2016). For the northern areas, Far Northern and Cairns / Cooktown, the values are less than 0.1. Between 2017 and 2018, the mean TSI on the entire GBR increased by 21%. The index reaches nearly 0.5.

Despite the low index values for the northern regions of the GBR, it can be seen that the Mackay / Capricorn region, south of the GBR, is relatively well preserved from thermal stress. The mean value for this region never falls below 0.6.



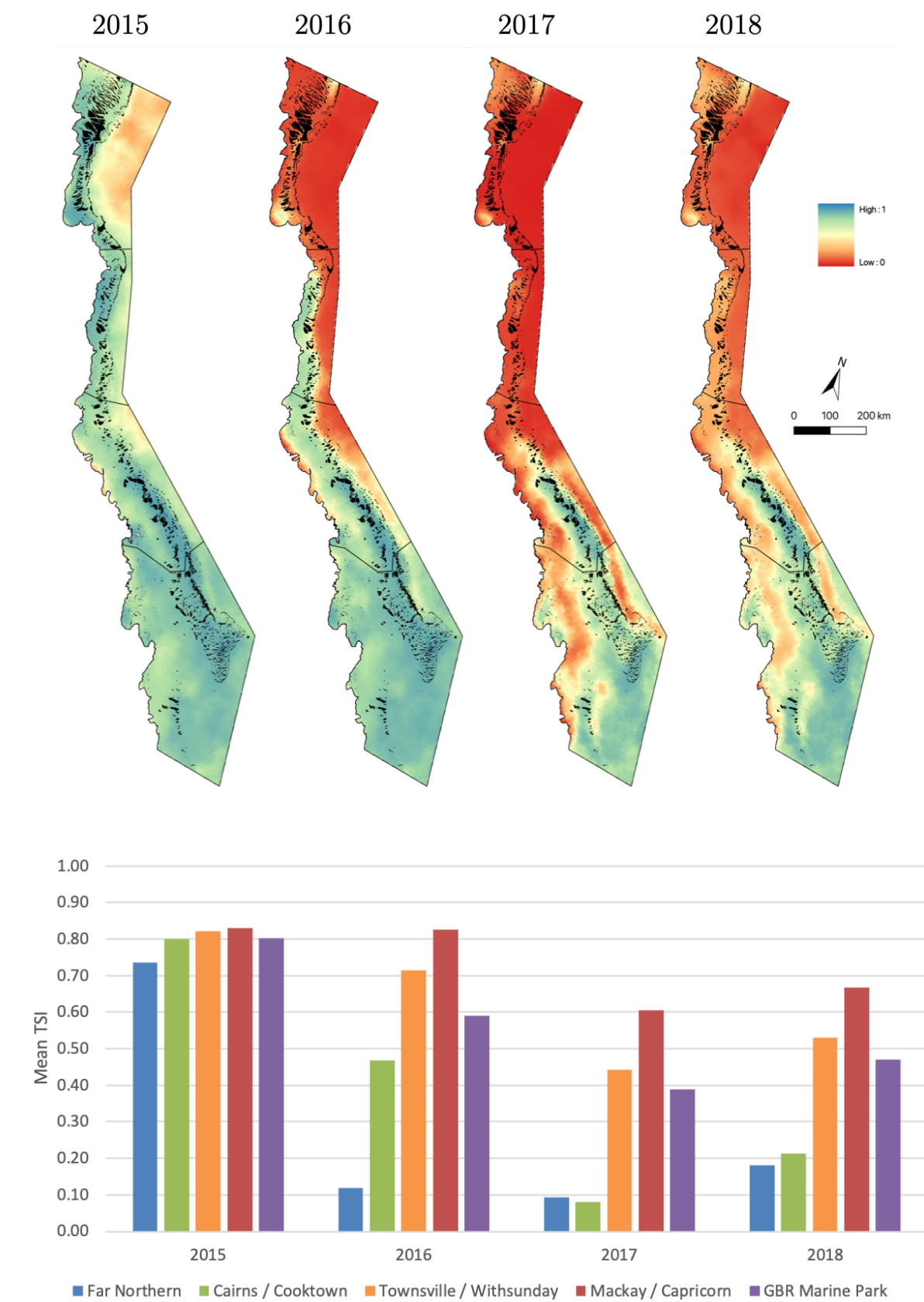


Figure 28: Evolution of the mean value of the Thermal Stress Index over the last 4 years for each GBR management unit and for the entire Marine Park. Data used for this graph are in Appendix H.

## 3.2 Cyclone Damage Index

Tropical cyclones are another major threat to coral reefs. Cyclone damage index (CDI) uses the information on the path and intensity of the 47 last major cyclones to calculate the loss of coral cover on the GBR. Fig. 29 shows the evolution of the CDI over the last 4 years.

The mean value of this index is very low. For the entire GBR, it is around 0.5 for the last 4 years. This low value is explained by the many cyclones that have impacted GBR in recent years. Between 2013 and 2018, 9 major cyclones caused damage to the reefs in GBR. Some of these have been very devastating and have a very high “Structural Damage Risk” index. As discussed in Section 2.1.2, this index takes into account several characteristics of the cyclone in order to estimate its destructive impact. It can be seen that since 2013, 5 cyclones have a significantly<sup>3</sup> high SDR.

With this index, it is possible to discern the damage area associated with the passage of major TCs. For example, in 2014, Tropical Cyclone Ita crossed the GBR Marine Park along the Queensland coast in central GBR. With winds up to 59 m/s, it is a category 5 cyclone causing heavy damage to coral reefs. The index made for 2015 makes it possible to assess this damage. Low index values are observed for the 2 central areas of the GBR: Cairns / Cooktown and Townsville / Withsunday. These areas have a mean CDI of 0.2 and minimum values of 0.06 and <0.01 respectively.

We can also observe the impact of Cyclone Marcia, which occurred in 2015 in the south of the GBR. Although the impact area is relatively small compared to Cyclone Ita, the high intensity of Marcia (58 m/s) caused significant damage to coral reefs in the Mackay / Capricorn region. The value of the CDI for this region is less than 0.2 for the year 2015.

In 2017, the mean CDI value for the Townsville / Withsunday region decreased by 40%. This decline in habitat quality is linked to the passage of Cyclone Debbie. Between 2017 and 2018, corals are no longer impacted by major cyclones and are recovering. The mean CDI value for the entire GBR increases by 20%.

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<sup>3</sup>By classifying the devastating impact of cyclones on the basis of their SDR. These 5 cyclones are among the 25% of the most devastating cyclones since 1985.

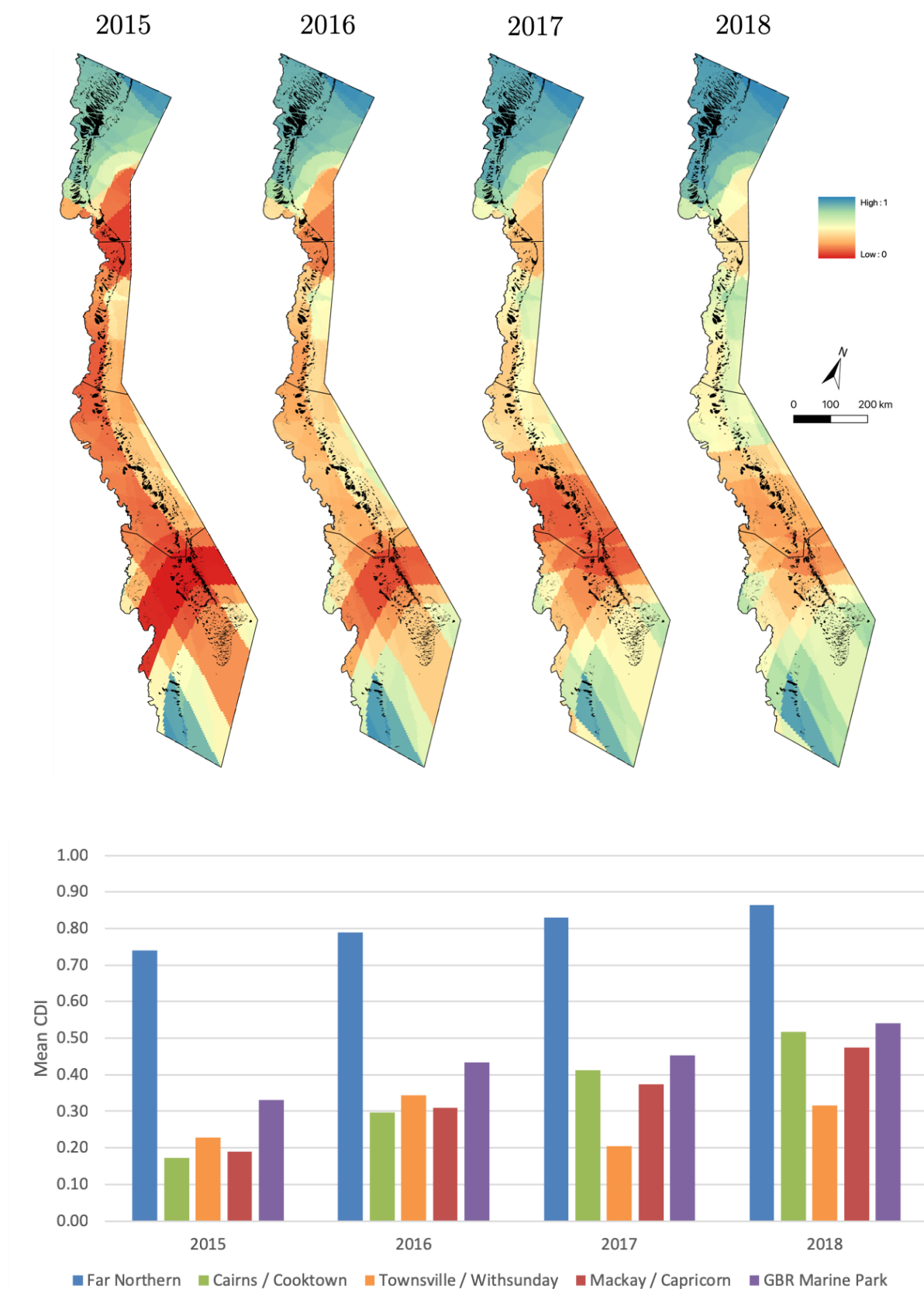


Figure 29: Evolution of the mean value of the Cyclone Damage Index over the last 4 years for each GBR management unit and for the entire Marine Park. Data used for this graph are in Appendix I.

### 3.3 COTS Outbreak Index

COTS outbreaks cause dramatic damage to coral populations. Identifying where they take place and their importance is essential to protect the GBR ecosystem. The COTS Outbreak Index (COI) developed in this thesis provides an overview of the temporal evolution of COTS outbreaks. Results for the last 4 years (2015 - 2018) are shown in Fig. 30.

In 2015, there are 2 main hotspots. The first one in the north of the Cairns / Cooktown area coincides with the location of the “COTS initiation box”. And the second is further south in the Mackay / Capricorn area. In general, the COI is quite high across the entire GBR. It has an average value of 0.9, which reflects good quality habitat.

In 2016, a new outbreak appeared in the central GBR between Cairns and Townsville. It can also be seen that the COI is declining in the southern part of the GBR. This is due to an increase in the density of COTS in this region.

In 2017, hotspots increased significantly. While in 2016, the minimum value of the COI on the entire GBR was 0.4, in 2017 it fell to about 0.2. However, it is important to note that outbreaks have not moved significantly.

In 2018, the outbreak in the Mackay / Capricorn region continues to intensify. The mean COI for this region fell by 12%. On the other hand, we observe that the outbreak present in the central part of the GBR is decreasing. It should be noted that the COI takes into account the recovery of coral, which for fast growing corals (such as *Acropora*) and in the absence of other threats, is estimated at about 10 years (Lawrey, 2014).

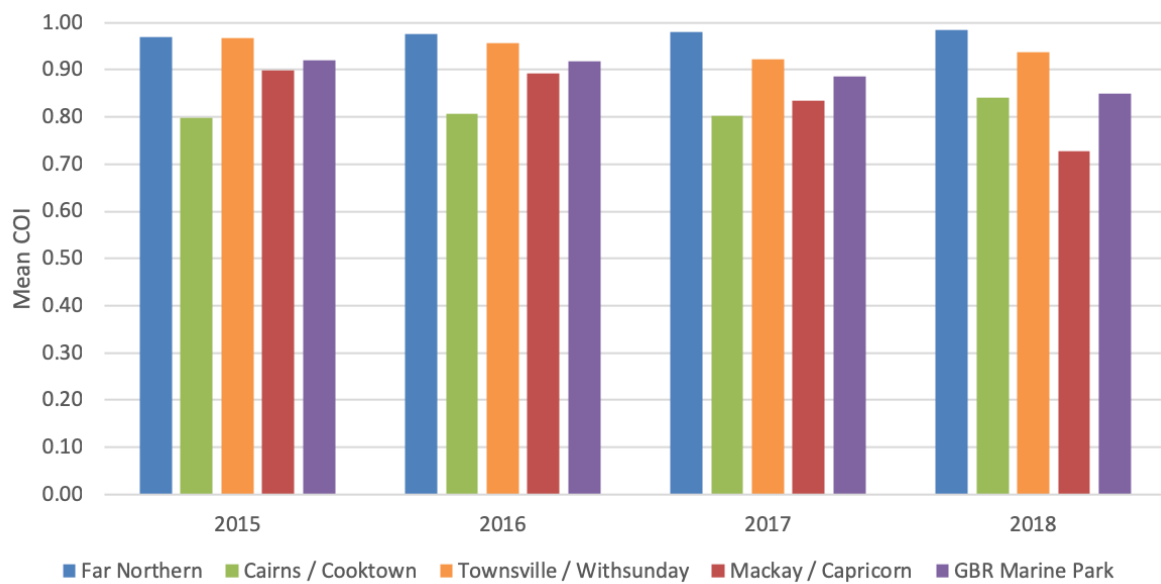
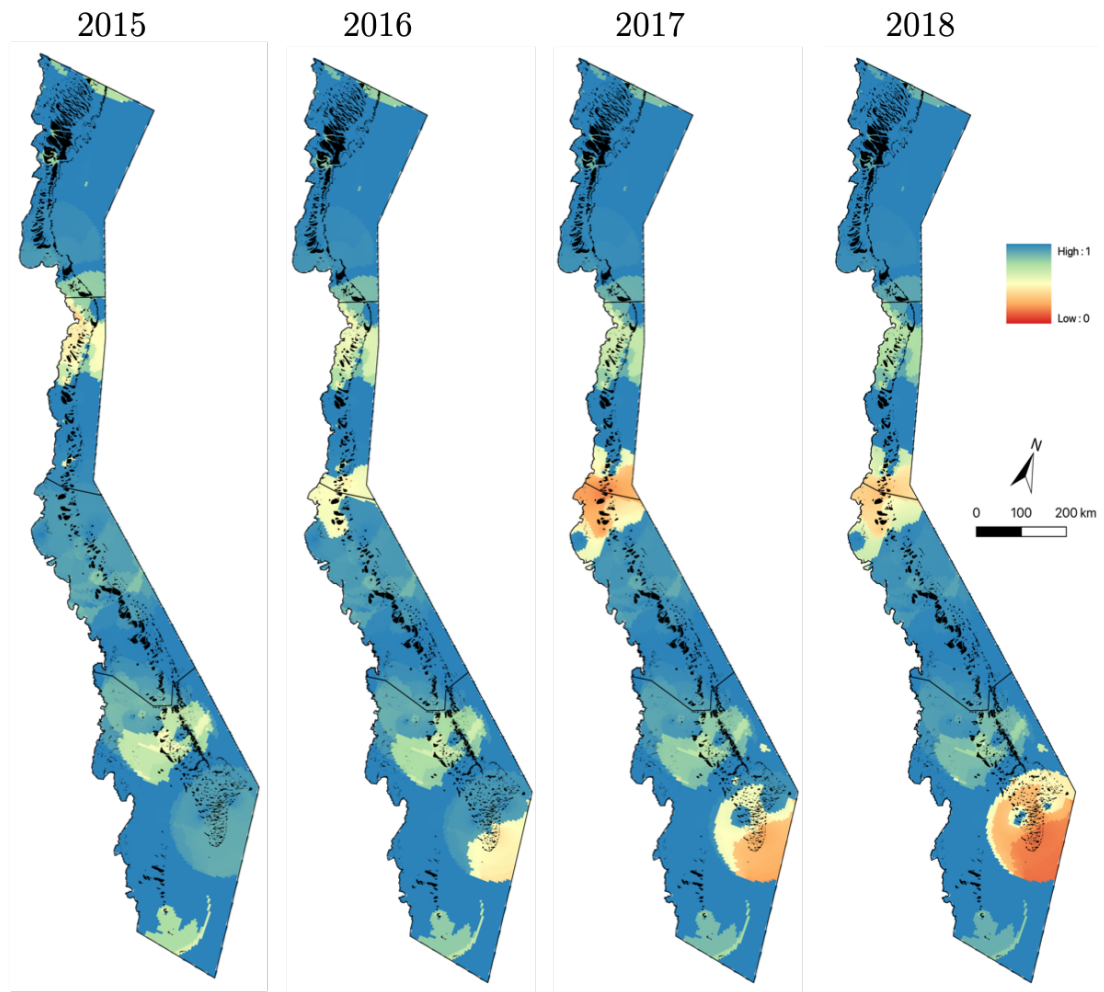


Figure 30: Evolution of the mean value of the COTS Outbreak Index over the last 4 years for each GBR management unit and for the entire Marine Park. Data used for this graph are in Appendix J.

### 3.4 Land-based Pollutants Index

The results presented in this section provide information on the discharge of land-based pollutants into the GBR Marine Park. These indices were created using modelled end-of-basin annual average total pollutants loads for each of the 35 GBR basins. The modelling represents an annual average based on the 1986-2014 flow period. As a result, we do not develop time series as we did for the other indices.

The Sediment Index (SI) illustrates the large amount of sediment released in the Townsville / Whitsunday area. The impacted area coincides with the mouth of the large Burdekin River. This river is one of the most important in Queensland and drains the vast Burdekin catchment. Each year, about 3260 kt of total suspended sediments are released into the ocean via this river. This river alone accounts for one-third of the total sediment released by all rivers flowing into the GBR.

Concerning the Nutrient Index (NI), there are 3 hotspots, related to nutrient discharges from the Johnstone, Burdekin and Fitzroy rivers. However, many other rivers in the central part of the GBR contain high nutrient loads. This is linked to the many sugar cane crops cultivated in the Burdekin and Wet Tropics regions.

The Pesticide Index (PI) looks similar to the NI. Indeed, the majority of pesticides come from intensive agriculture and mainly from sugarcane. About 45% of pesticides come from the following catchments: Haughton, Plane and Fitzroy.

Finally, the Land-based Pollutants Index (LPI) index is developed to take into account the impact of all land-based pollutants. It identifies the areas of the GBR where water quality is the poorest, with no distinction of the nature of the pollution.

Fig. 31 gives an overview of the mean value of each index for the 4 regions of the GBR. It can be seen that the Far Northern region has a mean index greater than 0.9 for each type of pollutant. Indeed, this area of the GBR is well preserved as the northern part of Queensland is mainly composed of protected natural areas. For each index, the central regions of Cairns/Cooktown and Townsville/Whitsunday are the most affected due to the high density of crops (dryland and irrigated) and sugarcane in neighbouring watersheds. For the Mackay / Capricorn region, most reefs are far offshore and therefore not strongly impacted by pollutants.

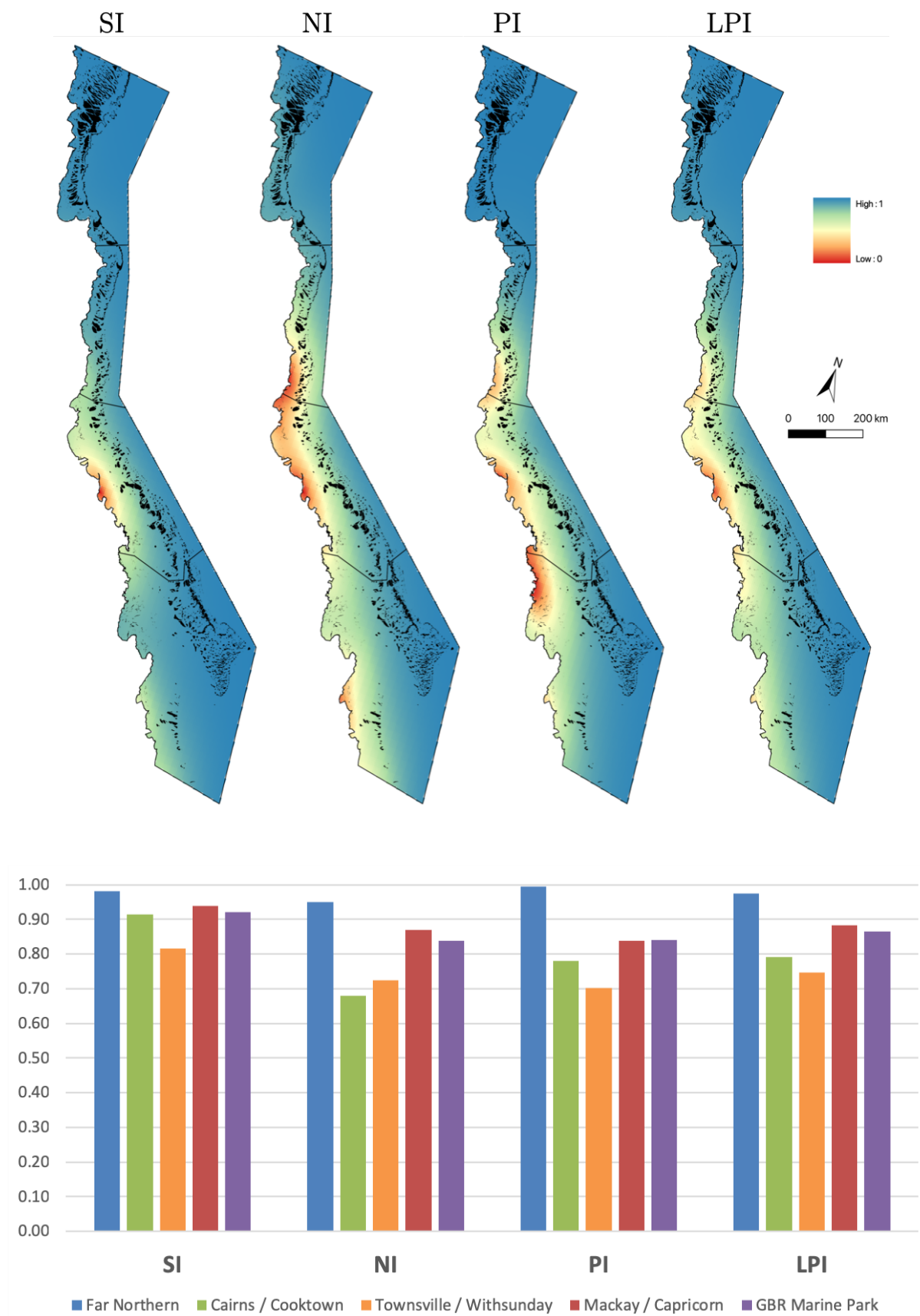


Figure 31: Mean value of the land-based pollutants indices for each region of the GBR and for the entire marine park. Data used for this graph are in Appendix K.

### 3.5 Global Habitat Quality Index

In order to determine the contribution of each threat, we have chosen to minimize the difference between the global Habitat Quality Index and the percentage of live coral cover (see Section 2.3). We have calibrated our index over the last 4 years. The optimal parameters obtained are shown in Table 6.

| Year            | $\alpha$ | $\beta$ | $\gamma$ | $\delta$ |
|-----------------|----------|---------|----------|----------|
| <b>2015</b>     | 4,66     | 0,16    | 1,25     | 0,00     |
| <b>2016</b>     | 0,57     | 0,68    | 0,20     | 1,91     |
| <b>2017</b>     | 0,34     | 0,89    | 0,58     | 2,80     |
| <b>2018</b>     | 0,51     | 1,77    | 0,56     | 1,63     |
| <b>Mean</b>     | 1,52     | 0,88    | 0,65     | 1,59     |
| <b>Variance</b> | 3,28     | 0,34    | 0,14     | 1,03     |

Table 6: Optimal parameters for HQI calculation, where  $\alpha$  represent the contribution of bleaching,  $\beta$  cyclones damages,  $\gamma$  COTS outbreaks and  $\delta$  land-based pollutants.

The means of the parameters are used in the following relation to calculate habitat quality in year  $t$  :

$$\text{HQI}_t = \text{TSI}_t^{1.52} \times \text{CDI}_t^{0.88} \times \text{COI}_t^{0.65} \times \text{LPI}^{1.59} \quad (12)$$

It is important to note that the calibration was done only for reefs where accurate information of the percentage of coral cover was measured by AIMS. For the years 2015 - 2018, this corresponds to respectively 50, 76, 47 and 44 reefs monitored. Given the small number of reefs used for calibration, we have developed maps representing the error between the HQI and the coral cover over the entire GBR<sup>4</sup> to assess the quality of the HQI (Fig. 32).

The maps shown in Fig. 32 represent the absolute value of the difference between the HQI and the coral cover. We observe that for the majority of GBR, the error is close to 0 (green areas), which means that HQI gives a good estimate of the coral cover. However, the error is high (close to 0.4) for some parts of the GBR, mainly the northern and southwestern area of the GBR Marine Park. For those areas, the HQI does not correctly reflect the coral cover. Histograms representing the distribution of errors are provided in Appendix L.

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<sup>4</sup>To obtain the coral cover over the entire GBR, a spatial interpolation (IDW) similar to that performed for COTS is used.



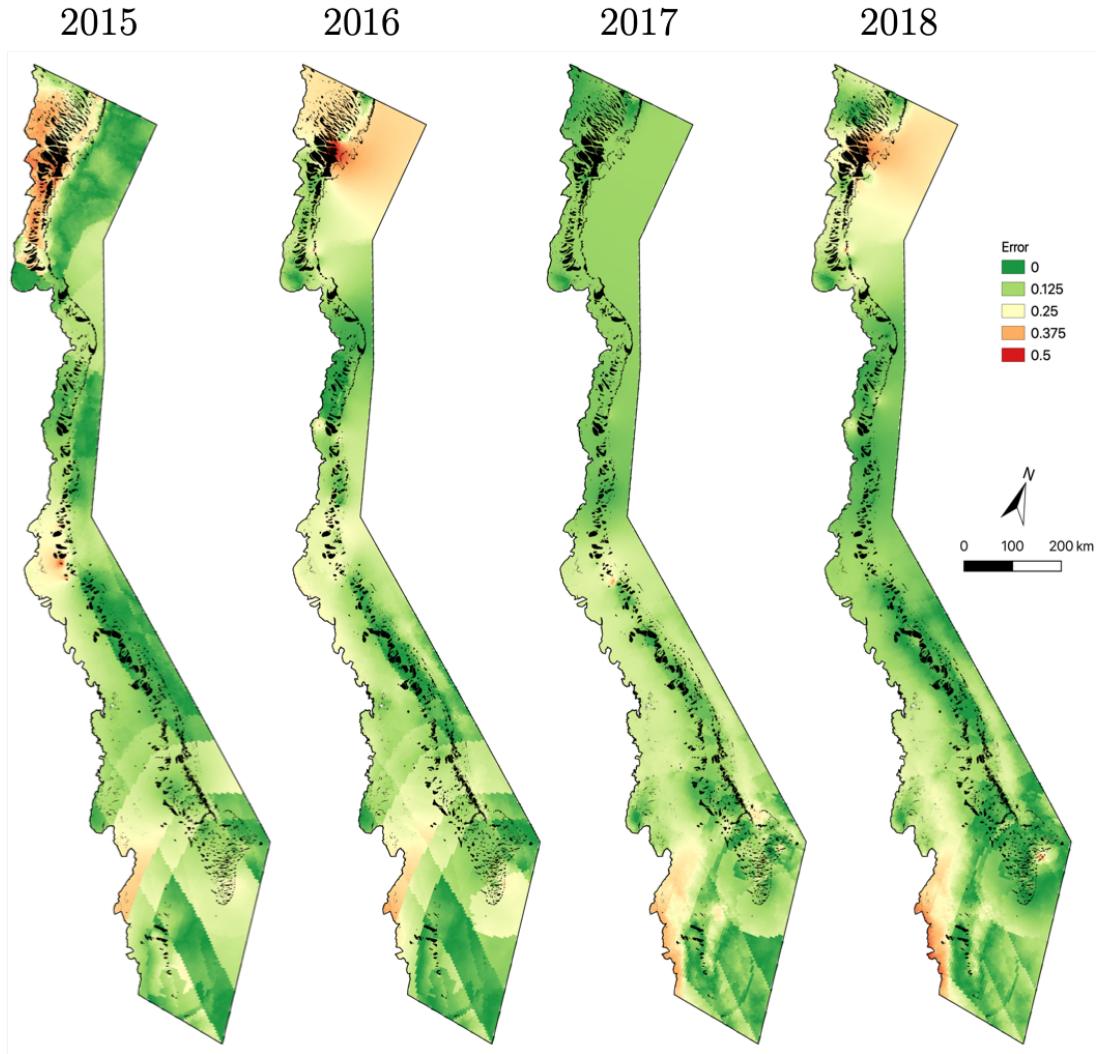


Figure 32: Errors between the Habitat Quality Index and the coral cover over the entire GBR for the last 4 years.

Thanks to the annual temporality of the indices (except for the land-based pollutants index), it is possible to calculate the HQI for each year since 1985. Fig. 33 shows the evolution of the index every 8 years from 1986 to 2018.

We can observe a general decline in habitat quality in the GBR. Between 1986 and 2018, the mean HQI decreased by 80%. Indeed, it goes from a value of 0.6 to 0.1.

It can be seen that before 2010, the Far Northern area was relatively well preserved, with an mean HQI of about 0.65. From 2010 onwards, the HQI begins to decline and in 2018, this area is one of the most threatened in the GBR.

Since 1986, the central region of the GBR has been under serious threat. In particular, the Townsville / Withsunday region whose mean HQI value for the 5 years illustrated in Fig. 33 is around 0.24.

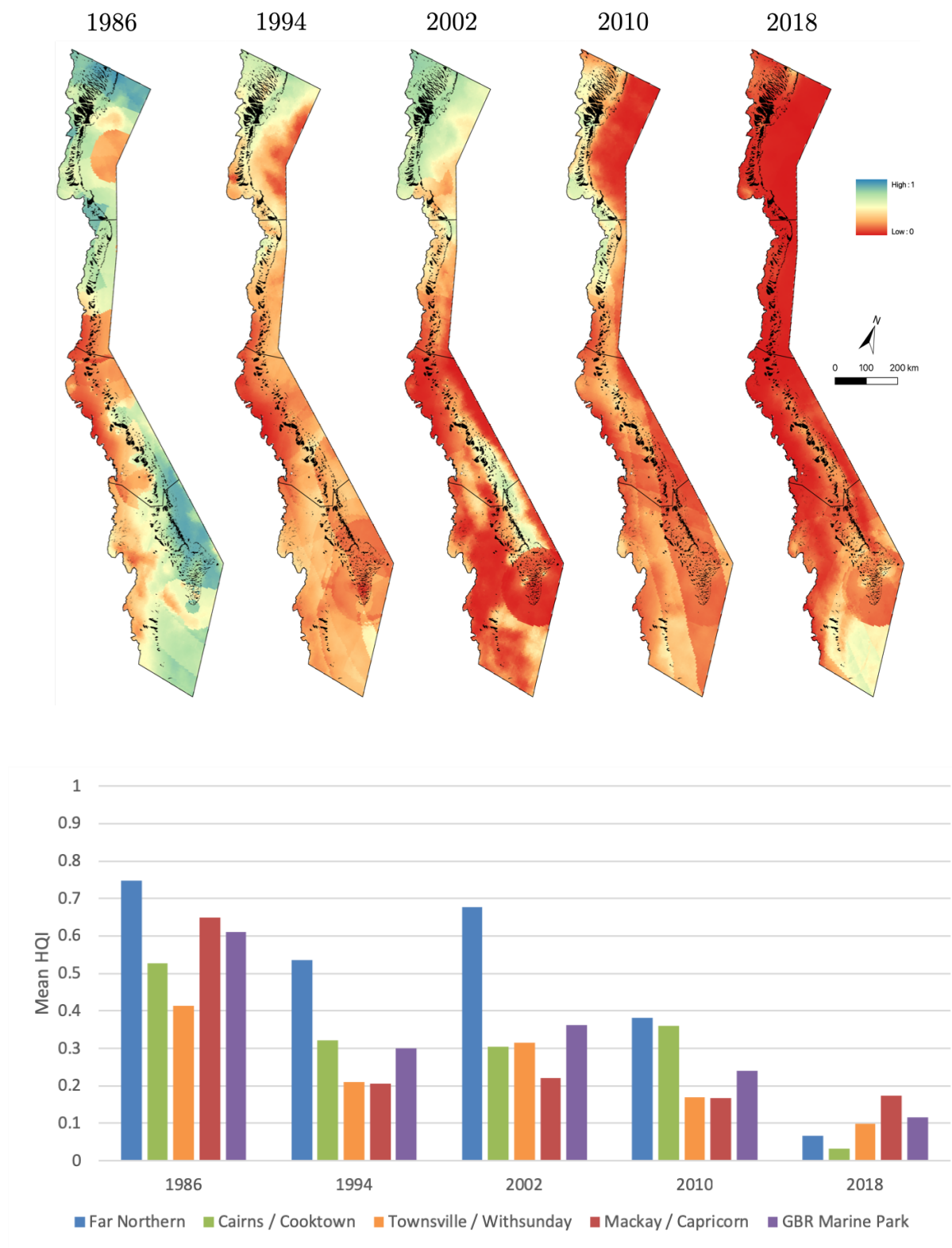


Figure 33: Mean value of the Habitat Quality Index since 1986 for each region of the GBR and for the entire Marine Park.

## 4 Discussion

This section concludes this thesis: it identifies the main results from our study and describes how they can be useful in the current context of GBR Marine Park conservation. This section also provides an opportunity to discuss the limitations of the indices. Indeed, many assumptions and simplifications have been made and must be kept in mind. Suggestions to improve the indices are given in order to promote potential future work on these indices.

### 4.1 Main results

The results obtained in this thesis reveal that habitat quality has been declining in recent years. For each of the indices we try to understand which events are responsible for this decline.

#### **Thermal stress**

The index developed as regard thermal stress (TSI) shows the impact of the dramatic bleaching event that took place in 2016. This bleaching event was the most severe ever encountered on the GBR Marine Park. The first 6 months of 2016 reached extremely high temperatures. This 6-month period was the planet's warmest half-year on record. This is the consequence of global warming but also of El Niño in the tropical Pacific that has increased sea surface temperature since October 2015. In March 2017, GBRMPA confirmed mass coral bleaching was occurring on the GBR for a second consecutive year (GBRMPA, 2017).

The succession of these 2 bleaching events is well represented by the TSI. Indeed, we observe extremely low values that reflect the dramatic effect of the 2 consecutive bleaching events in the northern part of the GBR. However, using a bleached reef mortality probability of 90% (see section 2.1.1) may be too high, which would explain having such low values. After the 2 consecutive bleaching events, the TSI increases, which reflects signs of coral recovery associated with a milder 2017-18 summer.

#### **Cyclone damage**

Unfortunately, thermal stress is not the only threat related to ocean warming. As the ocean warms, the high temperature of the sea boosts the energy of cyclones. According to Cheal et al. (2017), the consequences of climate change are more an increase in the intensity of cyclones than an increase in their frequency. More destructive cyclones will therefore become more and more frequent. The return time of cyclone sequences that cause extreme and widespread losses of corals could be reduced from hundreds of years to once every 25 years during this century. This represents a real threat to the state and recovery of coral reef ecosystems (AIMS, 2017).

For more than a decade and despite numerous cyclones and periods of record thermal stress, coral losses on the outer GBR have been small, localized and offset by gains on

undisturbed reefs. However, between 2009 and 2014, three unusually intense cyclones reduced the coral cover to record lows. Those tropical cyclones are Hamish in 2009, Yasi in 2011 and Ita in 2014 (Cheal et al., 2017). All three are included in the Cyclone Damage Index (CDI) and have a maximum intensity of about 60 m/s. Those are therefore force 5 cyclones that can cause up to 95% loss of coral cover.

The study conducted by Cheal et al. (2017) shows that ecological damage has been particularly severe in the south-central region where 68% of the coral cover has been destroyed over more than 1000 km. A record decline in species diversity and abundance of associated fish communities has been recorded. Four years later, in 2018, it can be seen that the recovery of average coral cover has been relatively slow. The observations of that study are consistent with the results we obtained in this thesis. Indeed, the CDI has extremely low values for the central and southern regions of the GBR, mainly in 2015, one year after the passage of Tropical Cyclone Yasi. The CDI also makes it possible to estimate the damage caused by more recent cyclones Marcia (in 2015) and Debbie (in 2017).

## **COTS outbreaks & land-based pollution**

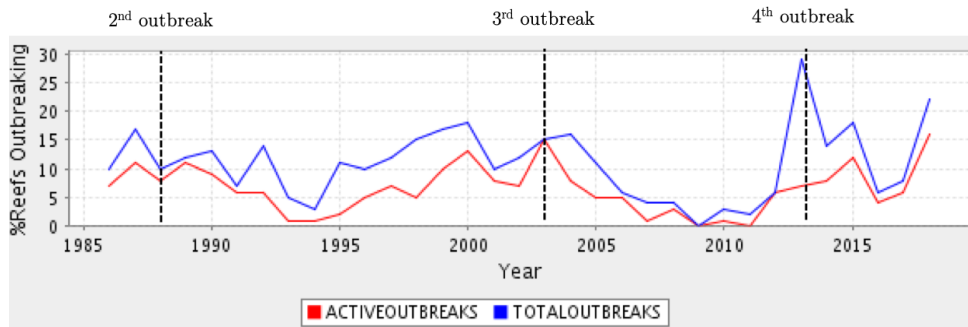
Over the past 50 years, major COTS outbreaks have originated on reefs in the area between Cairns and Lizard Island (Kenchington, 1977; Moran et al., 1992). In this region, the GBR is quite narrow and partly shallow. This leads to poor water quality due to land runoff and resuspension of sediment by wind. As a result, the level of nutrients and phytoplankton is quite high, allowing COTS larvae to survive more easily (Lawrey, 2014). The Nutrient Index (NI) developed in this thesis supports this statement. Indeed, it provides a good representation of the discharge from the Johnstone River located 75 km south of Cairns. This river discharges a very large amount of nutrients (nitrogen and phosphorus) into the ocean. The map illustrating the NI in Fig. 31 is correlated with the area where COTS appears. Recently, this area has been described as the “COTS initiation box” as shown in Appendix M (Pratchett et al., 2014). From there, outbreaks generally spread southward, taking nearly 10 years to move from the initiation area north of Cairns to the reefs offshore from the Whitsundays (Reichelt et al., 1990; Moran et al., 1992).

The GBR is currently experiencing the fourth COTS outbreak episode that began in 2011 and is still ongoing. Since 1986, AIMS has been launching an annual large-scale reef monitoring program for both COTS and corals, using the manta tow technique. The following figure shows the most recent historical data for the percentage of reefs affected by a COTS outbreak (Fig. 34a) and the average COTS densities (Fig. 34b) over the entire reef (AIMS, 2019). The first major outbreak that occurred between 1962 and 1975 is not shown on the graph.

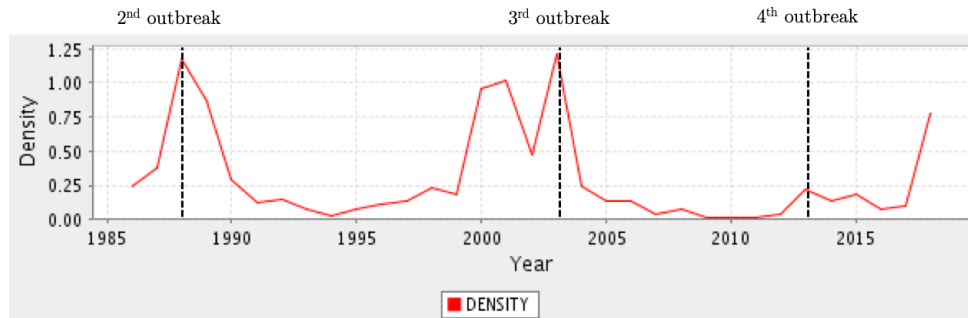
While the timing of the current outbreak is consistent with the 15-17 year cycle previously observed between outbreaks, there is a significant difference for this fourth outbreak. For the second (1979-1991) and third (1993-2006) outbreak episodes, COTS density and outbreak peaks showed a high degree of temporal synchrony. However, this trend seems to have broken down in the current outbreak. Indeed, data show that a significantly higher proportion of reefs are affected by COTS outbreaks (almost 30% of reefs), but that the average COTS density on reefs is significantly lower than in previous episodes. This observation may seem contradictory at first sight. In fact, it is entirely consistent with the current state of GBR, with the cover of live hard coral in the northern and

central parts of the GBR at the lowest levels ever recorded (Sweatman, 2018). As in any other predator-prey system (COTS - coral), the limited availability of prey (low hard coral cover) effectively reduces the number of its predators (COTS). However, even with these reduced population densities, COTS still have the potential to further decimate the available cover of live corals (Engelhardt, 2018).

Appendix N shows the COTS Outbreak Index (COI) for the 3 years in which the last 3 outbreaks were the most significant (shown as a black dotted line in Fig. 34). We noticed that for the first 2 episodes, the outbreak sites are localized but present a strong loss of coral cover linked to a high density of COTS, whereas for the last episode in 2013, the impact of COTS is more dispersed and less significant.



(a) Time-series plot of the percentage of reefs with COTS outbreaks across the GBR. *Credit: LTMP manta tow data 1986-2018, AIMS, 2019.*



(b) Time-series plot of the density\* of COTS on reefs across the GBR (\*density = mean number of COTS per 2 min. manta tow). *Credit: LTMP manta tow data 1986-2018, AIMS, 2019.*

Figure 34: Time-series data for the distribution of COTS outbreaks and mean COTS densities across the reef

## 4.2 Global Habitat Quality Index

To develop the global Habitat Quality Index (HQI), we based ourselves on the following premise: the percentage of living coral cover on a reef reflects the impact of all the threats it has experienced. The single-threat indices developed in this thesis give an indication of the loss in coral cover. These two statements gave us the idea to use coral cover data to calculate the HQI. Indeed, if we assume that each index perfectly reflects the loss of coral cover that a reef suffers for a specific threat, it would be enough to multiply them together to obtain the coral cover.

In order to take into account the assumptions and simplifications used to construct the indices, we have developed a relation that allows more flexibility: we assigned an exponent to each index (see Section 2.3). Then, we used the coral cover data to find the optimal exponents. These exponents can be interpreted as follows. If an exponent is greater than 1, it means that he decreases the index assigned to him. This is the case if the index underestimates the impact of the threat. Conversely, if the exponent is less than 1, the index assigned to him is increased. This means that the index estimates are too low, i.e. the loss of coral cover is too high. Finally, if the exponent is equal to 1, the index allows to correctly estimate the threat. The ideal is therefore to have values for exponent close to 1.

To calibrate the index, we have chosen to use the last 4 years (2015-2018), which are better representative of the current state of the GBR. Moreover, using recent years is more relevant because the indices of those years are the ones that reflect the most information on threats that have occurred since 1985 <sup>5</sup>.

The analysis of the optimal parameters (exponents) obtained (Table 6) makes it possible to reveal valuable information about the indices.

Concerning parameter  $\alpha$ , i.e. the exponent of the TSI, the 4-year mean value is 1.52. This value is higher than 1, so we can assume that the TSI estimates a loss of coral cover too low. However, further analysis shows that the reason this exponent is so high is because of the year 2015. Indeed, for this year, the TSI effectively underestimates the bleaching threat. On the other hand, the opposite is true for the years 2016, 2017 and 2018, where the exponent is significantly less than 1. The interpretation of this analysis would be to say that the value of 90% probability of mortality in case of severe bleaching is too high.

The parameter  $\beta$ , i.e. the CDI exponent, has a mean value of 0.88. This value suggests that the damage caused by cyclones is overestimated. This is not surprising given that we have assumed that the force of cyclones over their entire path in the GBR is equal to their maximum force. This hypothesis is discussed in the following section.

The exponent for the COI, the parameter  $\gamma$ , has a mean value of 0.65. This value, less than 1, may seem surprising because the average value of the COI for the entire GBR is close to 0.9. One might expect that the COI would tend to underestimate the threat of COTS outbreaks because it considers the quality of habitat to be very high. However, it should be kept in mind that calibration was only performed on reefs monitored by AIMS. Indeed, we use these reefs because they are the ones for which the coral cover is known with high precision. One hypothesis would be that AIMS does not choose the reefs they monitor at random and choose those for which the likelihood of COTS outbreaks is high. It therefore seems plausible that the COI values of the reefs used for calibration are very low because these reefs have a high COTS density. As a result, the index tends to overestimate the threat to these reefs.

Finally, the exponent for the LPI, the  $\delta$  parameter, is 1.59. This value means that the LPI underestimates the impact of the land-based pollution threat. This may be explained by the fact that most of the reefs used for calibration are not close to the coasts and are therefore located in areas where the LPI is very high. For the modelling of river plumes,

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<sup>5</sup>For example, the indices for the year 2018 are calculated taking into account all threats that have occurred since 1985. Of course, the recovery of corals is taken into account in the calculations.

many hypotheses had to be formulated. It is probable that for some reefs, the LPI estimates good habitat quality when this is not the case.

The resulting HQI can be used to improve coral connectivity estimates. As mentioned in section 1.4, connectivity is essential to ensure recovery, persistence and resilience of coral populations. For those reasons, it is interesting to incorporate it into spatial management strategies, such as Marine Protected Areas. The connectivity calculated by hydrodynamic models allows to calculate the dispersion of larvae by taking into account marine currents. This connectivity is called *potential* connectivity because it assumes that all conditions are ideal. Multiplying this potential connectivity by the HQI for the source reef and the settlement reef gives the *realised* connectivity as illustrated by the following relation :

$$C_{i,j}^* = HQI_i \times C_{i,j} \times HQI_j \quad (13)$$

where :

$C_{i,j}^*$  is the Realised connectivity

$C_{i,j}$  is the Potential connectivity

$HQI_i$  is the Habitat Quality Index of source reef  $i$

$HQI_j$  is the Habitat Quality Index of settlement reef  $j$

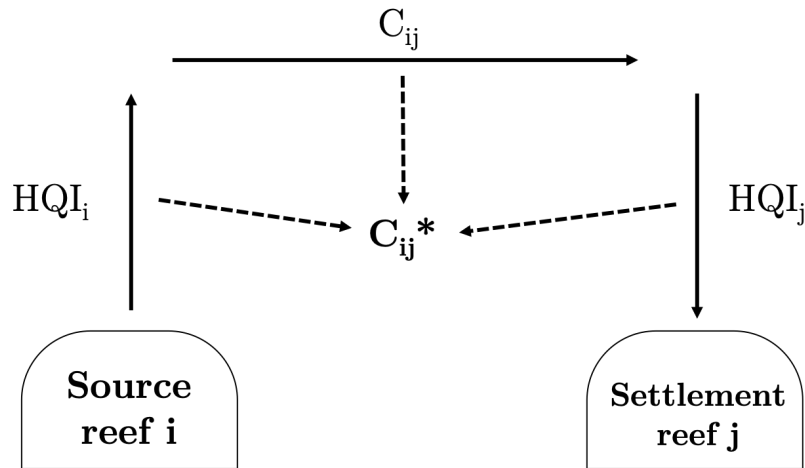


Figure 35: Potential and realised connectivity between two reefs. *Adapted from V. Chapaux*

The HQI can also be used to monitor the evolution of the GBR state. Indeed, it takes into account the year of occurrence of each threat and the reef recovery. This has the advantage of providing an index for each year. In addition, the historical legacy, i.e. the damage that has occurred on the reefs in previous years, is taken into account in considering the recovery of the reef. Indeed, a bleaching event that occurred 20 years ago has almost no impact on the current state of GBR, whereas if it occurred last year, its effects on habitat quality are still very significant. Threat trends can therefore be monitored over time.

### 4.3 Indices limitations and possible improvements

This section discusses the limitations of the four indices. Indeed, many hypotheses were made in order to develop each of them. It is important to be aware of this in order to use the indices carefully and to explore opportunities to improve them.

The index developed for thermal stress is based on degree heating week (DHW), an indicator that provides information on the duration and severity of sea temperature anomalies. Those data are obtained by remote sensing and have a spatial resolution of 5 km. The idea behind this index is to convert the DHW into the probability of bleaching and then use the probability of coral mortality in case of bleaching. Converting the DHW calculated by NOAA into a bleaching probability is well documented. However, concerning the probability of mortality, it is more difficult to find relevant information in the literature. We used the 90% value given by Wilkinson (2004) as the probability of mortality. This value is given as a maximum mortality probability, as in the case of severe bleaching event. In this thesis, coral cover loss is approximated as the product between the probability of mortality and the probability of bleaching (see Eq. 2). In practice, we assume that if the DHW is high, the probability of bleaching will be high (close to 1) and therefore the loss of coral cover will be close to 90%. On the other hand, if we observe a low DHW, we will calculate a bleaching probability close to 0 and therefore the percentage of coral cover loss will be close to 0%. Improvements can certainly be made in the way the loss of coral cover is calculated because we assume that probability of mortality equals percentage loss of coral cover, which is not necessarily correct. In addition, we do not take into account the fact that some coral species are more resistant to bleaching than others.

The index representing cyclone damage is calculated on the basis of the 47 major tropical cyclones that crossed the GBR between 1985 and 2018. It is quite difficult to know precisely how much damage a cyclone causes to corals. In this thesis, we calculated the wind intensity (m/s) for 3 zones around the cyclone path based on the maximum intensity of the cyclone. These 3 zones allow to approximate the wind profile. Ideally, it would be better to know the wind profile of each cyclone and instead of having a 3-zone decay, calculate a continuous decrease when moving away from the cyclone path. This could be a way to improve the index. Furthermore, we have assumed that each cyclone has the same force on its passage through GBR Marine Park. Obviously, in reality this is not the case, and this point could also be improved. Finally, we calculated the loss of coral cover according to the cyclonic category. This allowed us to link the intensity of the cyclone to the damage to the reefs. This method has the disadvantage of giving only 5 different indications of coral cover loss corresponding to the 5 categories of cyclones. Of course, it would be preferable to have a continuous relation between wind speed and coral cover loss.

The third index is the one concerning COTS outbreaks. It allows to calculate the loss of coral cover as a function of the COTS density. This relation is well documented. Data on COTS density are obtained through field surveys. Unfortunately, the reefs surveyed are not very numerous (about 100 out of 3800). Moreover, they are not systematically monitored every year. Therefore, we must use spatial and temporal interpolations to obtain data for all reefs in the GBR, resulting in many inaccuracies. Increasing the number of reefs surveyed would improve the quality of this index.



For each of the 3 indices described above, we assumed that 10 years after a threat (bleaching event, cyclone damage or COTS outbreak), the remaining fraction of dead coral is 10% of what it was just after the threat. This value is based on the general estimate of coral recovery time which is 10 years. Of course this value varies depending on both the coral species and the type of threat. In the framework of this thesis, we considered this approximation to be sufficient. However, to improve the indices, it might be interesting to improve this parameter.

Finally, the last index concerns the impact of land-based pollutants in the GBR Marine Park. Modelling the dispersion of those pollutants in the sea is extremely complex. Indeed, the irregular shape of the Queensland coast and the many ocean currents cause a very heterogeneous dispersion of pollutants. The index developed in the scope of this thesis gives a good idea of the areas where corals are most likely to be impacted by these pollutants, but it lacks both temporal and spatial accuracy. There is a temporal inaccuracy because the index uses average data and not annual data and a spatial inaccuracy because we approximate pollutant dispersion rather than use complex river plume models. Moreover, knowing the concentration of pollutants is not enough, it is also necessary to be able to quantify their effect on corals. Many improvements can therefore be considered for this index.

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# Appendices

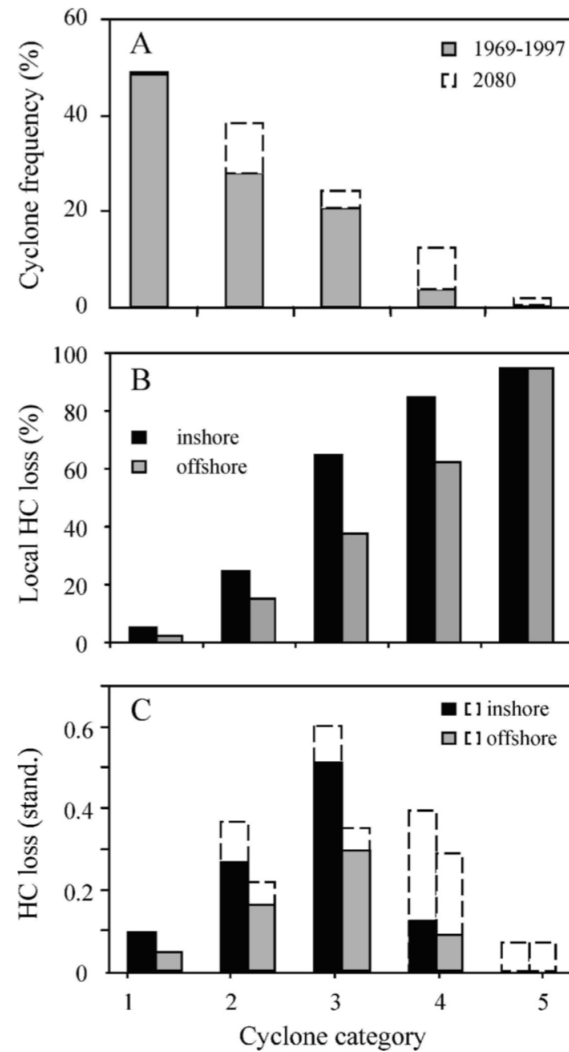
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## A Cyclones data

| Cyclone Name | Year | Circulation size (km) | Intensity (m/s) | Persistence (hrs) |
|--------------|------|-----------------------|-----------------|-------------------|
| Pierre       | 1985 | 137                   | 29              | 8                 |
| Tanya        | 1985 | 137                   | 30              | 24                |
| Manu         | 1986 | 165                   | 19              | 14                |
| Winifred     | 1986 | 204                   | 45              | 47                |
| Charlie      | 1988 | 137                   | 35              | 43                |
| Aivu         | 1989 | 269                   | 52              | 25                |
| Meena        | 1989 | 165                   | 17              | 4                 |
| Ivor         | 1990 | 262                   | 41              | 29                |
| Joy          | 1990 | 206                   | 52              | 85                |
| Kelvin       | 1991 | 287                   | 18              | 4                 |
| Fran         | 1992 | 313                   | 32              | 71                |
| Mark         | 1992 | 145                   | 22              | 7                 |
| Nina         | 1993 | 296                   | 20              | 41                |
| Oliver       | 1993 | 319                   | 46              | 39                |
| Rewa         | 1994 | 199                   | 41              | 44                |
| Celeste      | 1996 | 154                   | 40              | 16                |
| Ethel        | 1996 | 65                    | 30              | 12                |
| Ita          | 1997 | 167                   | 21              | 6                 |
| Justin       | 1997 | 439                   | 22              | 50                |
| Nathan       | 1998 | 121                   | 23              | 35                |
| Rona         | 1999 | 288                   | 39              | 14                |
| Steve        | 2000 | 104                   | 33              | 11                |
| Tessi        | 2000 | 187                   | 28              | 12                |
| Abigail      | 2001 | 228                   | 23              | 5                 |
| Fritz        | 2004 | 148                   | 20              | 5                 |
| Ingrid       | 2005 | 120                   | 54              | 22                |
| Jim          | 2006 | 130                   | 18              | 5                 |
| Kate         | 2006 | 152                   | 24              | 8                 |
| Larry        | 2006 | 159                   | 68              | 10                |
| Monica       | 2006 | 226                   | 42              | 23                |
| Guba         | 2007 | 105                   | 29              | 12                |
| Ellie        | 2009 | 120                   | 23              | 19                |
| Hamish       | 2009 | 217                   | 62              | 31                |
| Olga         | 2010 | 136                   | 32              | 19                |
| Ului         | 2010 | 148                   | 43              | 10                |
| Anthony      | 2011 | 176                   | 29              | 10                |
| Tasha        | 2010 | 136                   | 22              | 7                 |
| Yasi         | 2011 | 322                   | 61              | 17                |
| Oswald       | 2013 | 376                   | 18              | 54                |
| Tim          | 2013 | 337                   | 26              | 17                |
| Zane         | 2013 | 94                    | 31              | 6                 |
| Dylan        | 2014 | 495                   | 28              | 36                |
| Edna         | 2014 | 134                   | 20              | 2                 |
| Ita          | 2014 | 208                   | 59              | 37                |
| Marcia       | 2015 | 154                   | 58              | 19                |
| Nathan       | 2015 | 139                   | 46              | 87                |
| Debbie       | 2017 | 250*                  | 54*             | 84*               |

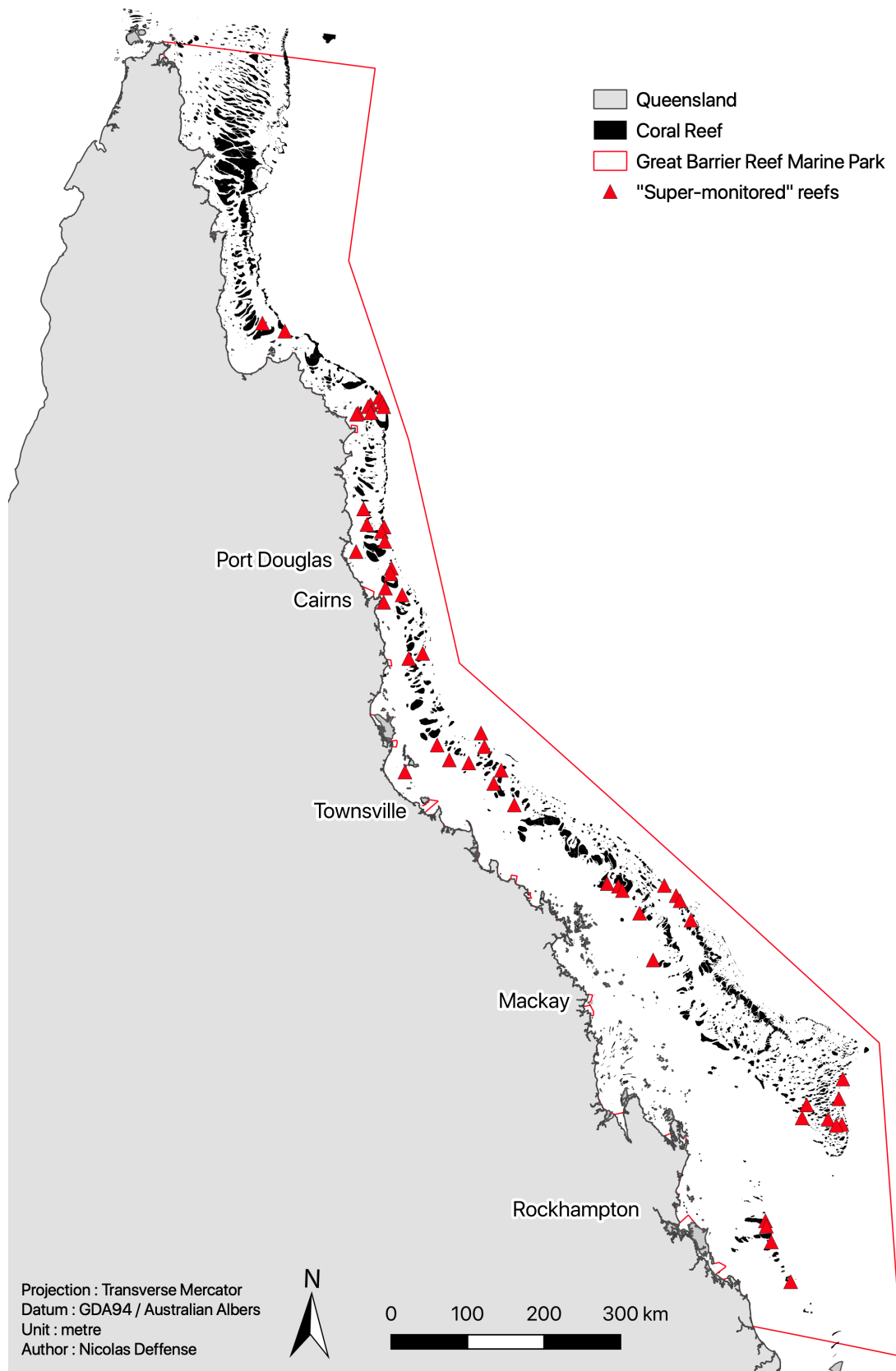
Year of occurrence, circulation size, intensity and persistence of the 47 TC's used for the Cyclone Damage Index. Fields marked with an asterisk are estimated values. *Credit: Puotinen et al. (2016).*

## B Cyclone impacts on coral reefs



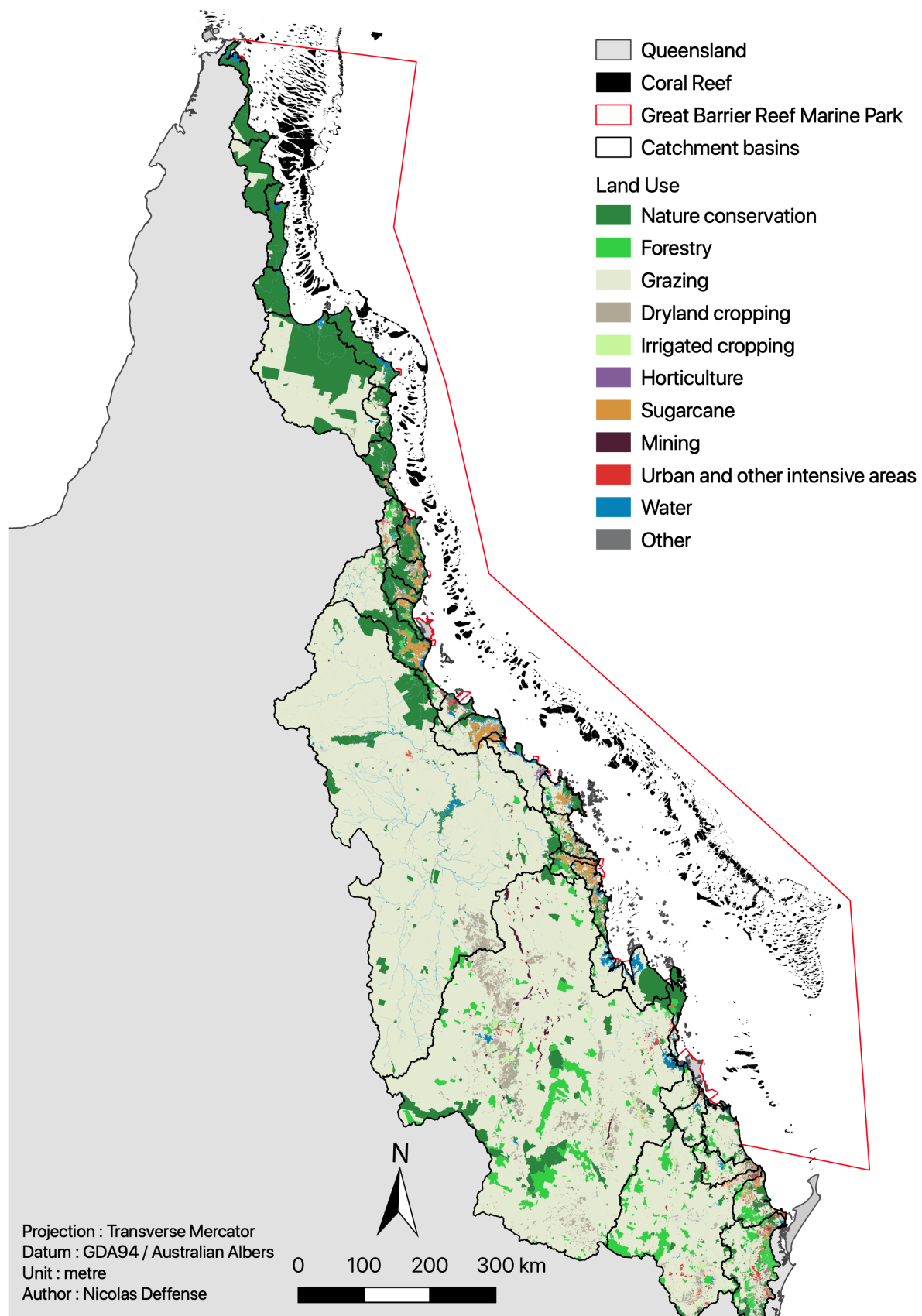
Observed and predicted cyclone intensity distribution, and changes in coral cover by tropical cyclones on the GBR. (A) Frequency distribution of tropical cyclones on the GBR as observed between 1969 and 1997 (Puotinen et al. 1997; gray bars), and with an increase in cyclone intensity of half a category as predicted for 2080 (Knutson and Tuleya 2004; white dashed bars). (B) Observed local loss in coral cover in response to cyclone intensity on inshore and offshore reefs. (C) GBR-wide loss of coral cover on inshore and offshore reefs, at cyclone intensity distributions as observed 1969–1997 (black and gray bars), and as predicted for 2080 (white dashed bars). *Credit: Fabricius et al. (2008).*

## C “*Super-monitored*” reefs



Location of the 52 reefs that have been monitored at least *15 times since 1985* and have been monitored at least *once since 2016*. In the framework of this thesis, these reefs are called “*super-monitored*” reefs.

## D Queensland Land Use



Land use of all catchment basins that discharge into GBR Marine Park

## E Land-based Pollutants

| Catchment name   | Sediments    |             | Nutrients   |             | Pesticides   |
|------------------|--------------|-------------|-------------|-------------|--------------|
|                  | Total TSS    | Total DIN   | Total PN    | Total PP    | Total PSII   |
|                  | load (kt/yr) | load (t/yr) | load (t/yr) | load (t/yr) | load (kg/yr) |
| Baffle           | 80           | 60          | 270         | 130         | 10           |
| Kolan            | 40           | 80          | 100         | 40          | 70           |
| Burnett          | 550          | 250         | 670         | 270         | 120          |
| Burrum           | 30           | 200         | 60          | 20          | 80           |
| Mary             | 770          | 460         | 2900        | 970         | 70           |
| Black            | 60           | 100         | 140         | 80          | 5            |
| Ross             | 60           | 180         | 100         | 50          | 5            |
| Haughton         | 180          | 1020        | 220         | 140         | 1710         |
| Burdekin         | 3260         | 1100        | 2890        | 1800        | 500          |
| Don              | 210          | 180         | 310         | 170         | 180          |
| Jacky Jacky      | 50           | 70          | 270         | 40          | 0            |
| Olive Pascoe     | 70           | 100         | 450         | 70          | 0            |
| Lockhart         | 70           | 50          | 320         | 100         | 0            |
| Stewart          | 50           | 30          | 150         | 50          | 0            |
| Normanby         | 190          | 100         | 250         | 80          | 10           |
| Jeannie          | 40           | 30          | 200         | 40          | 0            |
| Endeavour        | 60           | 40          | 250         | 80          | 5            |
| Styx             | 100          | 90          | 830         | 430         | 200          |
| Shoalwater       | 70           | 100         | 650         | 310         | 110          |
| Water Park       | 60           | 70          | 1270        | 520         | 20           |
| Fitzroy          | 1510         | 800         | 3070        | 1820        | 1750         |
| Calliope         | 60           | 50          | 440         | 220         | 100          |
| Boyne            | 20           | 40          | 110         | 60          | 40           |
| Proserpine       | 130          | 310         | 390         | 160         | 330          |
| O'Connell        | 310          | 320         | 840         | 420         | 970          |
| Pioneer          | 230          | 260         | 450         | 180         | 980          |
| Plane            | 150          | 460         | 470         | 230         | 1760         |
| Daintree         | 100          | 480         | 580         | 80          | 120          |
| Mossman          | 20           | 160         | 100         | 20          | 80           |
| Barron           | 60           | 150         | 200         | 50          | 120          |
| Mulgrave-Russell | 250          | 930         | 1230        | 280         | 750          |
| Johnstone        | 380          | 1060        | 1990        | 760         | 920          |
| Tully            | 160          | 780         | 870         | 180         | 490          |
| Murray           | 70           | 410         | 400         | 80          | 370          |
| Herbert          | 480          | 1520        | 1330        | 290         | 250          |

Modelled end-of-catchment annual average pollutant loads exported to the coast for each of the 35 GBR catchments. Annual average are based on the 1986-2014 flow period. *Credit: Bartley et al. (2017b).*

## F Regions & catchments

| Region            | Basin/Catchment name | Basin Area (km2) |
|-------------------|----------------------|------------------|
| Brunett Mary      | Burnett              | 33274            |
|                   | Kolan                | 2891             |
|                   | Burrum               | 3346             |
|                   | Baffle               | 4101             |
|                   | Mary                 | 9420             |
| Burdekin          | Burdekin             | 130120           |
|                   | Ross                 | 1707             |
|                   | Don                  | 3736             |
|                   | Black                | 1057             |
|                   | Haughton             | 4051             |
| Cape York         | Normanby             | 24380            |
|                   | Jeannie              | 3637             |
|                   | Stewart              | 2770             |
|                   | Jacky Jacky          | 2990             |
|                   | Olive-Pascoe         | 4172             |
|                   | Lockhart             | 2873             |
|                   | Endeavour            | 2186             |
| Fitzroy           | Fitzroy              | 142144           |
|                   | Boyne                | 2498             |
|                   | Calliope             | 2416             |
|                   | Shoalwater           | 3614             |
|                   | Styx                 | 2997             |
|                   | Water Park           | 1846             |
| Mackay Whitsunday | Proserpine           | 2513             |
|                   | Plane                | 2547             |
|                   | Pioneer              | 1664             |
|                   | O'Connell            | 2305             |
| Wet Tropics       | Barron               | 2188             |
|                   | Herbert              | 9852             |
|                   | Daintree             | 2105             |
|                   | Mossman              | 477              |
|                   | Murray               | 1125             |
|                   | Tully                | 1668             |
|                   | Mulgrave-Russell     | 1975             |
|                   | Johnstone            | 2317             |

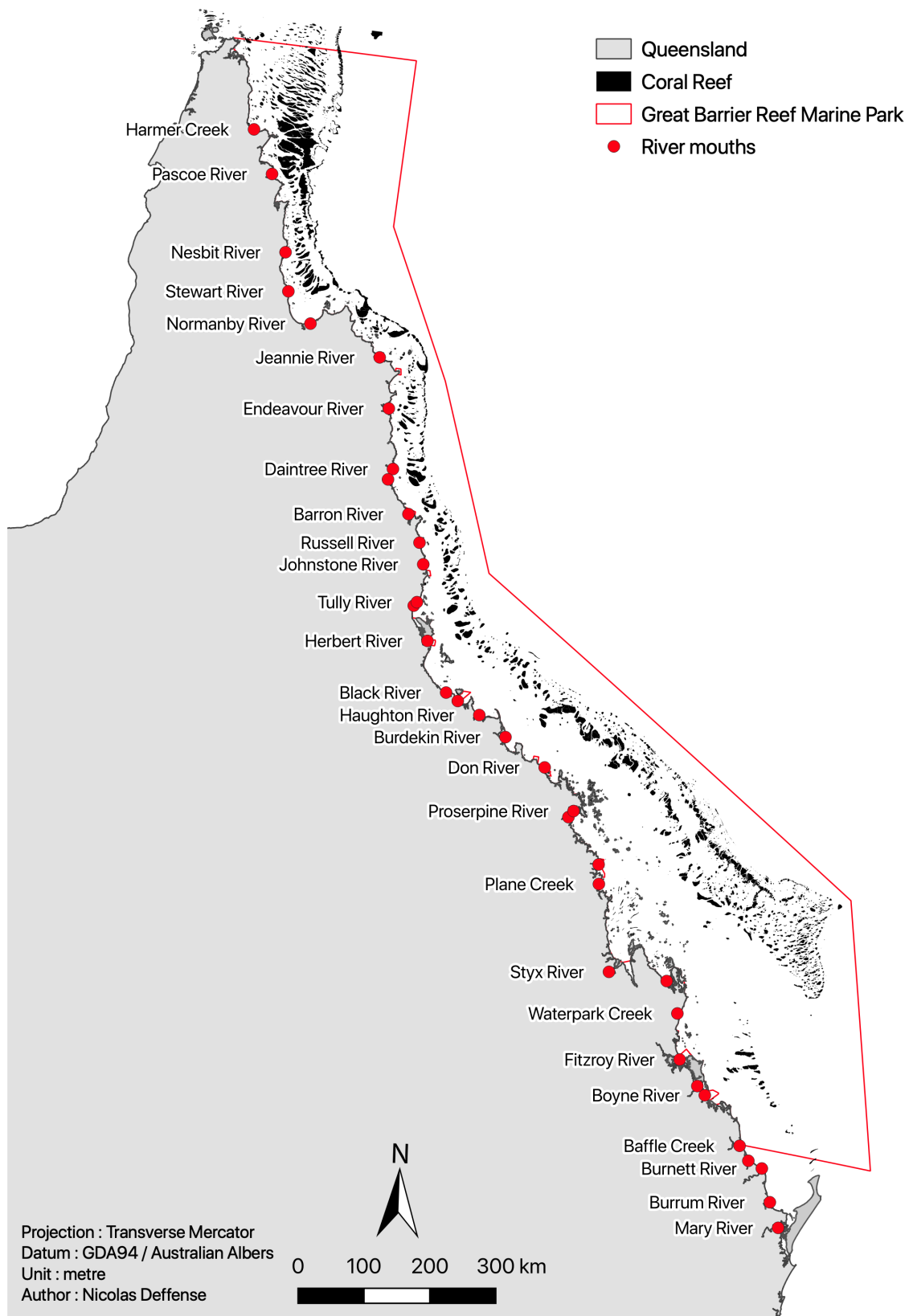
Summary of the 35 catchments of the Great Barrier Reef and their area classified by Region



## G River mouths

| Catchment        | River            | X           | Y           |
|------------------|------------------|-------------|-------------|
| Baffle           | Baffle Creek     | 1997015,338 | -2804854,11 |
| Barron           | Barron River     | 1467619,14  | -1875525,66 |
| Black            | Black River      | 1533420,983 | -2141023,1  |
| Boyne            | Boyne River      | 1942226,974 | -2730917,98 |
| Burdekin         | Burdekin River   | 1624713,303 | -2204680,37 |
| Burnett          | Burnett River    | 2031535,857 | -2837738,91 |
| Burrum           | Burrum River     | 2045313,422 | -2887927,37 |
| Calliope         | Calliope River   | 1930537,966 | -2717563,76 |
| Daintree         | Daintree River   | 1442061,315 | -1808811,81 |
| Don              | Don River        | 1685050,26  | -2248073,08 |
| Endeavour        | Endeavour River  | 1432691,344 | -1718391,86 |
| Fitzroy          | Fitzroy River    | 1902681,668 | -2678738,39 |
| Haughton         | Haughton River   | 1584308,997 | -2172990,21 |
| Herbert          | Herbert River    | 1502763,026 | -2064539,21 |
| Jacky Jacky      | Harmer Creek     | 1216036,638 | -1307101,02 |
| Jeannie          | Jeannie River    | 1416309,715 | -1642212,13 |
| Johnstone        | Johnstone River  | 1492458,795 | -1950082,93 |
| Kolan            | Kolan River      | 2010898,66  | -2826899,42 |
| Lockhart         | Nesbit River     | 1269722,408 | -1489585,74 |
| Mary             | Mary River       | 2059034,831 | -2925798,9  |
| Mossman          | Mossman River    | 1435203,207 | -1824663    |
| Mulgrave-Russell | Russell River    | 1485688,829 | -1917773,91 |
| Murray           | Murray River     | 1480368,748 | -2012452,15 |
| Normanby         | Normanby River   | 1310794,913 | -1595249,1  |
| O'Connell        | O'Connell River  | 1723291,647 | -2321307,71 |
| Olive-Pascoe     | Pascoe River     | 1245396,755 | -1373000,96 |
| Pioneer          | Pioneer River    | 1770974,491 | -2390712,09 |
| Plane            | Plane Creek      | 1772409,091 | -2419994,13 |
| Proserpine       | Proserpine River | 1730639,029 | -2311885,24 |
| Ross             | Ross River       | 1551332,459 | -2153054,52 |
| Shoalwater       | Shoalwater Creek | 1879089,814 | -2561801,45 |
| Stewart          | Stewart River    | 1275981,337 | -1547997,61 |
| Styx             | Styx River       | 1792112,81  | -2551057,48 |
| Tully            | Tully River      | 1484961,683 | -2007074,16 |
| Waterpark        | Waterpark Creek  | 1896837,255 | -2609826,18 |

Summary of the 35 rivers that drain the GBR Catchments Area and the coordinates of their mouths



Location of the mouths of the 35 major rivers that discharge into the GBR Marine Park

## H Thermal Stress Index - Statistics

|        | Far Northern | Cairns /<br>Cooktown | Townsville /<br>Whitsunday | Mackay /<br>Capricorn | GBR Marine<br>Park |
|--------|--------------|----------------------|----------------------------|-----------------------|--------------------|
| Min    | 0,451        | 0,653                | 0,300                      | 0,585                 | 0,300              |
| Max    | 0,897        | 0,899                | 0,911                      | 0,901                 | 0,911              |
| Mean   | 0,736        | 0,800                | 0,821                      | 0,830                 | 0,802              |
| Median | 0,741        | 0,799                | 0,845                      | 0,850                 | 0,823              |
| Var    | 0,008        | 0,003                | 0,007                      | 0,003                 | 0,007              |
| Std    | 0,089        | 0,052                | 0,084                      | 0,056                 | 0,081              |

Statistic of year 2015

|        | Far Northern | Cairns /<br>Cooktown | Townsville /<br>Whitsunday | Mackay /<br>Capricorn | GBR Marine<br>Park |
|--------|--------------|----------------------|----------------------------|-----------------------|--------------------|
| Min    | 0,055        | 0,082                | 0,066                      | 0,475                 | 0,055              |
| Max    | 0,559        | 0,792                | 0,906                      | 0,902                 | 0,906              |
| Mean   | 0,118        | 0,469                | 0,715                      | 0,825                 | 0,590              |
| Median | 0,094        | 0,544                | 0,763                      | 0,847                 | 0,757              |
| Var    | 0,004        | 0,065                | 0,028                      | 0,004                 | 0,099              |
| Std    | 0,067        | 0,255                | 0,168                      | 0,064                 | 0,315              |

Statistic of year 2016

|        | Far Northern | Cairns /<br>Cooktown | Townsville /<br>Whitsunday | Mackay /<br>Capricorn | GBR Marine<br>Park |
|--------|--------------|----------------------|----------------------------|-----------------------|--------------------|
| Min    | 0,019        | 0,025                | 0,019                      | 0,089                 | 0,019              |
| Max    | 0,475        | 0,242                | 0,894                      | 0,878                 | 0,894              |
| Mean   | 0,094        | 0,080                | 0,442                      | 0,605                 | 0,388              |
| Median | 0,069        | 0,078                | 0,324                      | 0,658                 | 0,290              |
| Var    | 0,005        | 0,001                | 0,085                      | 0,041                 | 0,090              |
| Std    | 0,072        | 0,037                | 0,292                      | 0,202                 | 0,300              |

Statistic of year 2017

|        | Far Northern | Cairns /<br>Cooktown | Townsville /<br>Whitsunday | Mackay /<br>Capricorn | GBR Marine<br>Park |
|--------|--------------|----------------------|----------------------------|-----------------------|--------------------|
| Min    | 0,069        | 0,110                | 0,076                      | 0,065                 | 0,065              |
| Max    | 0,554        | 0,376                | 0,900                      | 0,888                 | 0,900              |
| Mean   | 0,181        | 0,212                | 0,530                      | 0,668                 | 0,470              |
| Median | 0,164        | 0,229                | 0,438                      | 0,713                 | 0,414              |
| Var    | 0,005        | 0,003                | 0,060                      | 0,028                 | 0,072              |
| Std    | 0,072        | 0,058                | 0,245                      | 0,167                 | 0,268              |

Statistic of year 2018

# I Cyclone Damage Index - Statistics

|        | Far Northern | Cairns /<br>Cooktown | Townsville /<br>Whitsunday | Mackay /<br>Capricorn | GBR Marine<br>Park |
|--------|--------------|----------------------|----------------------------|-----------------------|--------------------|
| Min    | 0,070        | 0,065                | 0,008                      | 0,007                 | 0,007              |
| Max    | 0,961        | 0,543                | 0,385                      | 0,935                 | 0,961              |
| Mean   | 0,740        | 0,173                | 0,228                      | 0,190                 | 0,332              |
| Median | 0,827        | 0,173                | 0,189                      | 0,194                 | 0,204              |
| Var    | 0,048        | 0,010                | 0,007                      | 0,029                 | 0,082              |
| Std    | 0,220        | 0,098                | 0,086                      | 0,171                 | 0,286              |

Statistic of year 2015

|        | Far Northern | Cairns /<br>Cooktown | Townsville /<br>Whitsunday | Mackay /<br>Capricorn | GBR Marine<br>Park |
|--------|--------------|----------------------|----------------------------|-----------------------|--------------------|
| Min    | 0,177        | 0,168                | 0,077                      | 0,069                 | 0,069              |
| Max    | 0,969        | 0,636                | 0,489                      | 0,949                 | 0,969              |
| Mean   | 0,788        | 0,296                | 0,344                      | 0,309                 | 0,433              |
| Median | 0,864        | 0,309                | 0,328                      | 0,336                 | 0,352              |
| Var    | 0,037        | 0,010                | 0,006                      | 0,029                 | 0,065              |
| Std    | 0,192        | 0,101                | 0,079                      | 0,169                 | 0,255              |

Statistic of year 2016

|        | Far Northern | Cairns /<br>Cooktown | Townsville /<br>Whitsunday | Mackay /<br>Capricorn | GBR Marine<br>Park |
|--------|--------------|----------------------|----------------------------|-----------------------|--------------------|
| Min    | 0,297        | 0,285                | 0,076                      | 0,082                 | 0,076              |
| Max    | 0,976        | 0,711                | 0,531                      | 0,938                 | 0,976              |
| Mean   | 0,830        | 0,413                | 0,205                      | 0,374                 | 0,453              |
| Median | 0,894        | 0,430                | 0,146                      | 0,426                 | 0,436              |
| Var    | 0,026        | 0,009                | 0,014                      | 0,036                 | 0,077              |
| Std    | 0,163        | 0,095                | 0,118                      | 0,189                 | 0,277              |

Statistic of year 2017

|        | Far Northern | Cairns /<br>Cooktown | Townsville /<br>Whitsunday | Mackay /<br>Capricorn | GBR Marine<br>Park |
|--------|--------------|----------------------|----------------------------|-----------------------|--------------------|
| Min    | 0,414        | 0,401                | 0,164                      | 0,167                 | 0,164              |
| Max    | 0,981        | 0,772                | 0,616                      | 0,952                 | 0,981              |
| Mean   | 0,864        | 0,518                | 0,316                      | 0,475                 | 0,541              |
| Median | 0,917        | 0,537                | 0,263                      | 0,534                 | 0,542              |
| Var    | 0,018        | 0,007                | 0,013                      | 0,032                 | 0,060              |
| Std    | 0,135        | 0,085                | 0,114                      | 0,180                 | 0,246              |

Statistic of year 2018

## J COTS Outbreak Index - Statistics

|        | Far Northern | Cairns /<br>Cooktown | Townsville /<br>Whitsunday | Mackay /<br>Capricorn | GBR Marine<br>Park |
|--------|--------------|----------------------|----------------------------|-----------------------|--------------------|
| Min    | 0,608        | 0,377                | 0,715                      | 0,449                 | 0,377              |
| Max    | 1,000        | 1,000                | 1,000                      | 1,000                 | 1,000              |
| Mean   | 0,968        | 0,797                | 0,967                      | 0,898                 | 0,920              |
| Median | 1,000        | 0,975                | 0,974                      | 0,929                 | 0,968              |
| Var    | 0,005        | 0,050                | 0,001                      | 0,013                 | 0,015              |
| Std    | 0,073        | 0,223                | 0,037                      | 0,113                 | 0,124              |

Statistic of year 2015

|        | Far Northern | Cairns /<br>Cooktown | Townsville /<br>Whitsunday | Mackay /<br>Capricorn | GBR Marine<br>Park |
|--------|--------------|----------------------|----------------------------|-----------------------|--------------------|
| Min    | 0,686        | 0,457                | 0,475                      | 0,394                 | 0,394              |
| Max    | 1,000        | 1,000                | 1,000                      | 1,000                 | 1,000              |
| Mean   | 0,975        | 0,808                | 0,957                      | 0,892                 | 0,918              |
| Median | 1,000        | 0,831                | 0,980                      | 0,945                 | 0,972              |
| Var    | 0,003        | 0,037                | 0,008                      | 0,020                 | 0,018              |
| Std    | 0,057        | 0,192                | 0,092                      | 0,141                 | 0,134              |

Statistic of year 2016

|        | Far Northern | Cairns /<br>Cooktown | Townsville /<br>Whitsunday | Mackay /<br>Capricorn | GBR Marine<br>Park |
|--------|--------------|----------------------|----------------------------|-----------------------|--------------------|
| Min    | 0,750        | 0,174                | 0,184                      | 0,233                 | 0,174              |
| Max    | 1,000        | 1,000                | 1,000                      | 1,000                 | 1,000              |
| Mean   | 0,981        | 0,803                | 0,922                      | 0,835                 | 0,886              |
| Median | 1,000        | 0,860                | 0,983                      | 0,955                 | 0,978              |
| Var    | 0,002        | 0,046                | 0,033                      | 0,047                 | 0,037              |
| Std    | 0,045        | 0,215                | 0,181                      | 0,216                 | 0,192              |

Statistic of year 2017

|        | Far Northern | Cairns /<br>Cooktown | Townsville /<br>Whitsunday | Mackay /<br>Capricorn | GBR Marine<br>Park |
|--------|--------------|----------------------|----------------------------|-----------------------|--------------------|
| Min    | 0,803        | 0,306                | 0,316                      | 0,148                 | 0,148              |
| Max    | 1,000        | 1,000                | 1,000                      | 1,000                 | 1,000              |
| Mean   | 0,985        | 0,842                | 0,938                      | 0,728                 | 0,849              |
| Median | 1,000        | 0,890                | 0,987                      | 0,874                 | 0,982              |
| Var    | 0,001        | 0,031                | 0,022                      | 0,091                 | 0,060              |
| Std    | 0,035        | 0,176                | 0,147                      | 0,302                 | 0,245              |

Statistic of year 2018

## K Land-based Pollutants Index - Statistics

|        | Far Northern | Cairns /<br>Cooktown | Townsville /<br>Whitsunday | Mackay /<br>Capricorn | GBR Marine<br>Park |
|--------|--------------|----------------------|----------------------------|-----------------------|--------------------|
| Min    | 0,946        | 0,745                | 0,163                      | 0,594                 | 0,163              |
| Max    | 0,999        | 0,977                | 0,980                      | 0,997                 | 0,999              |
| Mean   | 0,982        | 0,915                | 0,817                      | 0,938                 | 0,920              |
| Median | 0,987        | 0,929                | 0,846                      | 0,979                 | 0,968              |
| Var    | 0,000        | 0,003                | 0,017                      | 0,007                 | 0,010              |
| Std    | 0,014        | 0,053                | 0,132                      | 0,082                 | 0,102              |

Statistic for Sediment Index (SI)

|        | Far Northern | Cairns /<br>Cooktown | Townsville /<br>Whitsunday | Mackay /<br>Capricorn | GBR Marine<br>Park |
|--------|--------------|----------------------|----------------------------|-----------------------|--------------------|
| Min    | 0,885        | 0,096                | 0,114                      | 0,151                 | 0,096              |
| Max    | 0,996        | 0,930                | 0,964                      | 0,995                 | 0,996              |
| Mean   | 0,950        | 0,680                | 0,724                      | 0,870                 | 0,838              |
| Median | 0,956        | 0,715                | 0,777                      | 0,956                 | 0,923              |
| Var    | 0,001        | 0,039                | 0,043                      | 0,028                 | 0,035              |
| Std    | 0,034        | 0,197                | 0,207                      | 0,167                 | 0,186              |

Statistic for Nutrient Index (NI)

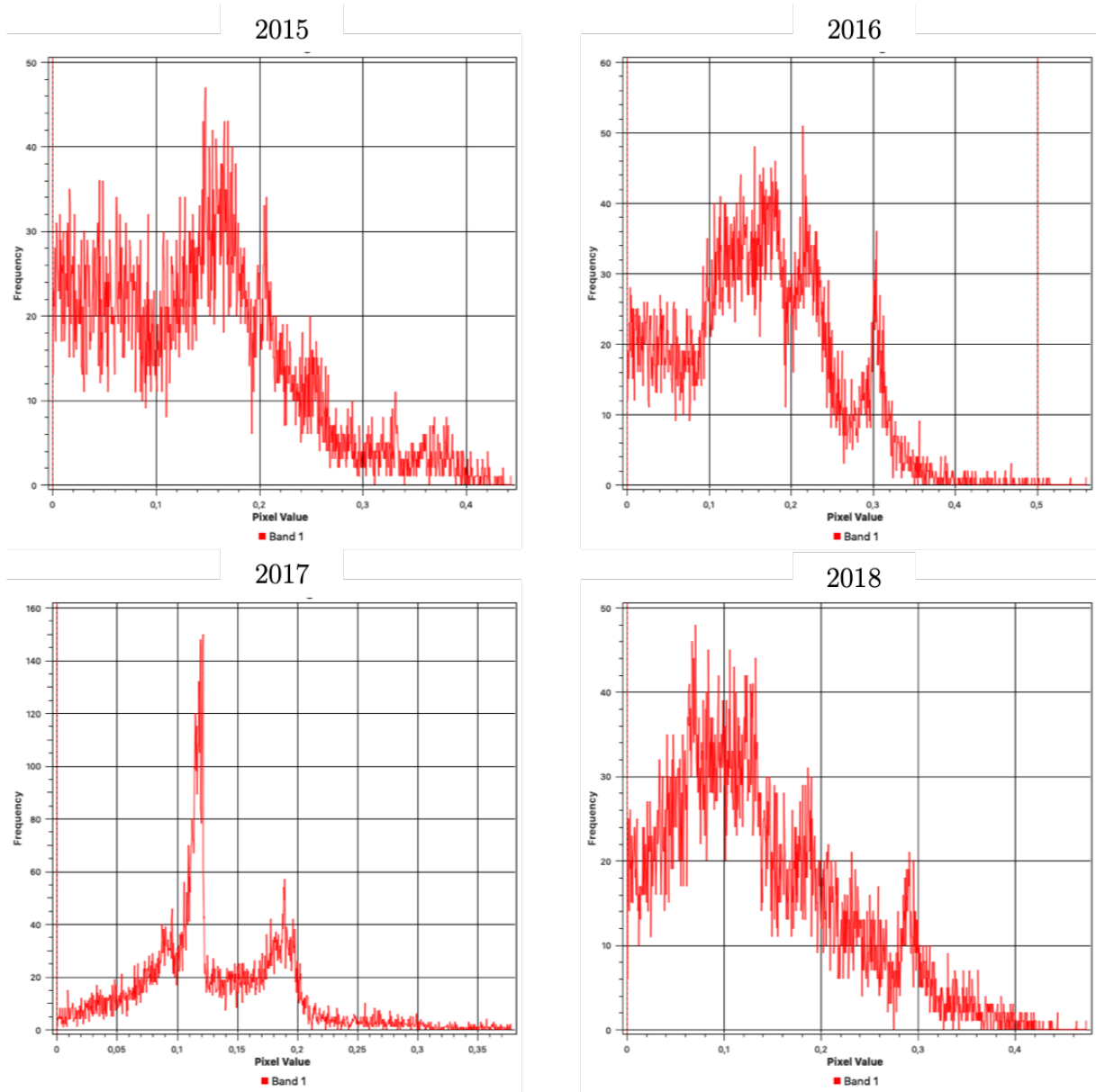
|        | Far Northern | Cairns /<br>Cooktown | Townsville /<br>Whitsunday | Mackay /<br>Capricorn | GBR Marine<br>Park |
|--------|--------------|----------------------|----------------------------|-----------------------|--------------------|
| Min    | 0,965        | 0,309                | 0,128                      | 0,000                 | 0,000              |
| Max    | 1,000        | 0,974                | 0,953                      | 0,994                 | 1,000              |
| Mean   | 0,996        | 0,780                | 0,701                      | 0,838                 | 0,841              |
| Median | 0,999        | 0,819                | 0,768                      | 0,954                 | 0,949              |
| Var    | 0,000        | 0,028                | 0,038                      | 0,053                 | 0,045              |
| Std    | 0,008        | 0,167                | 0,196                      | 0,230                 | 0,211              |

Statistic for Pesticide Index (PI)

|        | Far Northern | Cairns /<br>Cooktown | Townsville /<br>Whitsunday | Mackay /<br>Capricorn | GBR Marine<br>Park |
|--------|--------------|----------------------|----------------------------|-----------------------|--------------------|
| Min    | 0,937        | 0,386                | 0,209                      | 0,374                 | 0,209              |
| Max    | 0,998        | 0,959                | 0,966                      | 0,996                 | 0,998              |
| Mean   | 0,976        | 0,791                | 0,747                      | 0,882                 | 0,866              |
| Median | 0,980        | 0,822                | 0,795                      | 0,963                 | 0,952              |
| Var    | 0,000        | 0,019                | 0,030                      | 0,024                 | 0,026              |
| Std    | 0,018        | 0,139                | 0,172                      | 0,155                 | 0,160              |

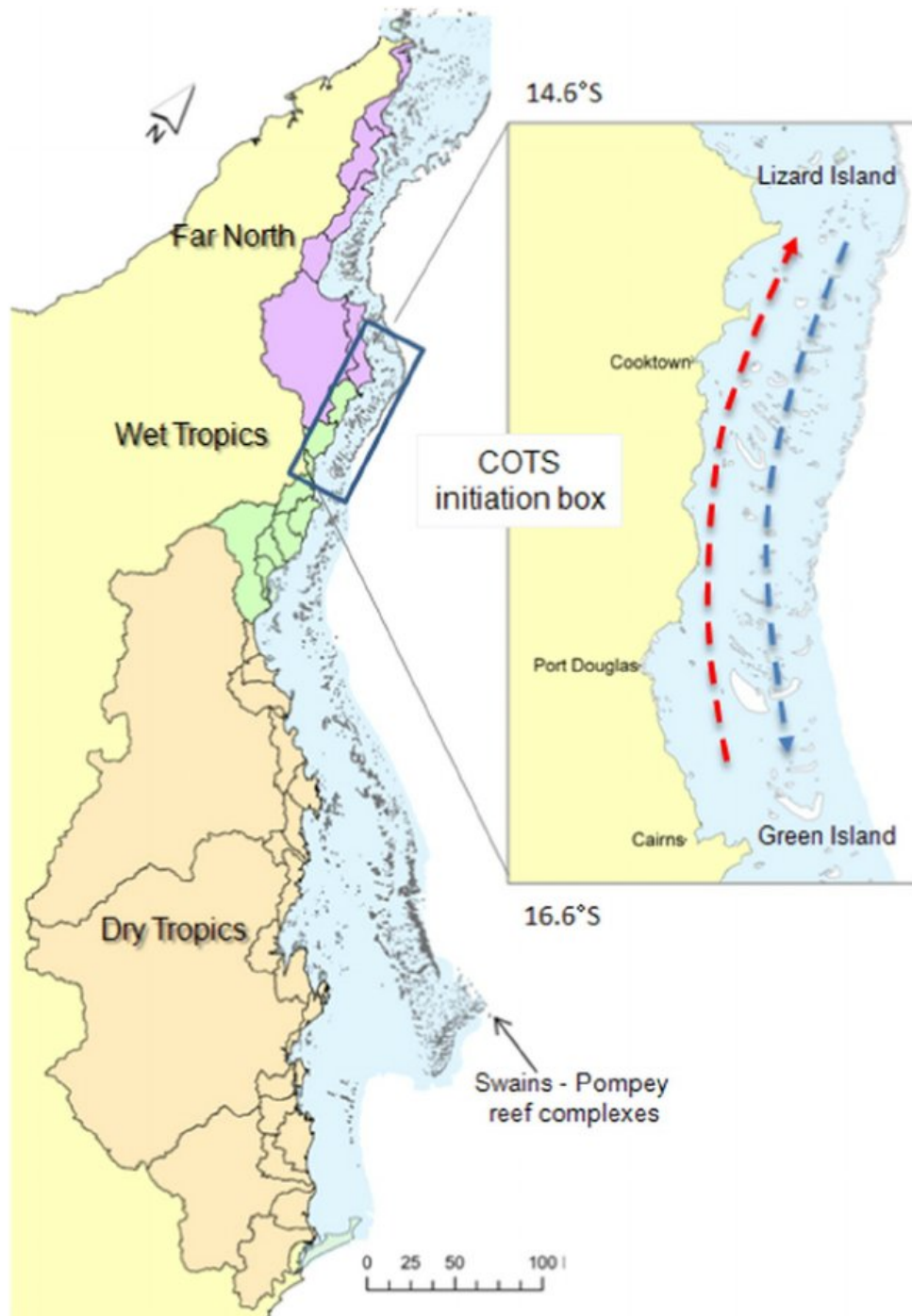
Statistic for Land-based Pollutants Index (LPI)

## L Histograms of calibration errors



Histograms representing the distribution of errors between the Habitat Quality Index and the coral cover for the last 4 years. Errors are calculated according to the following relationship for each year  $t$ :  $\text{Err} = |HQI_t - CC_t|$

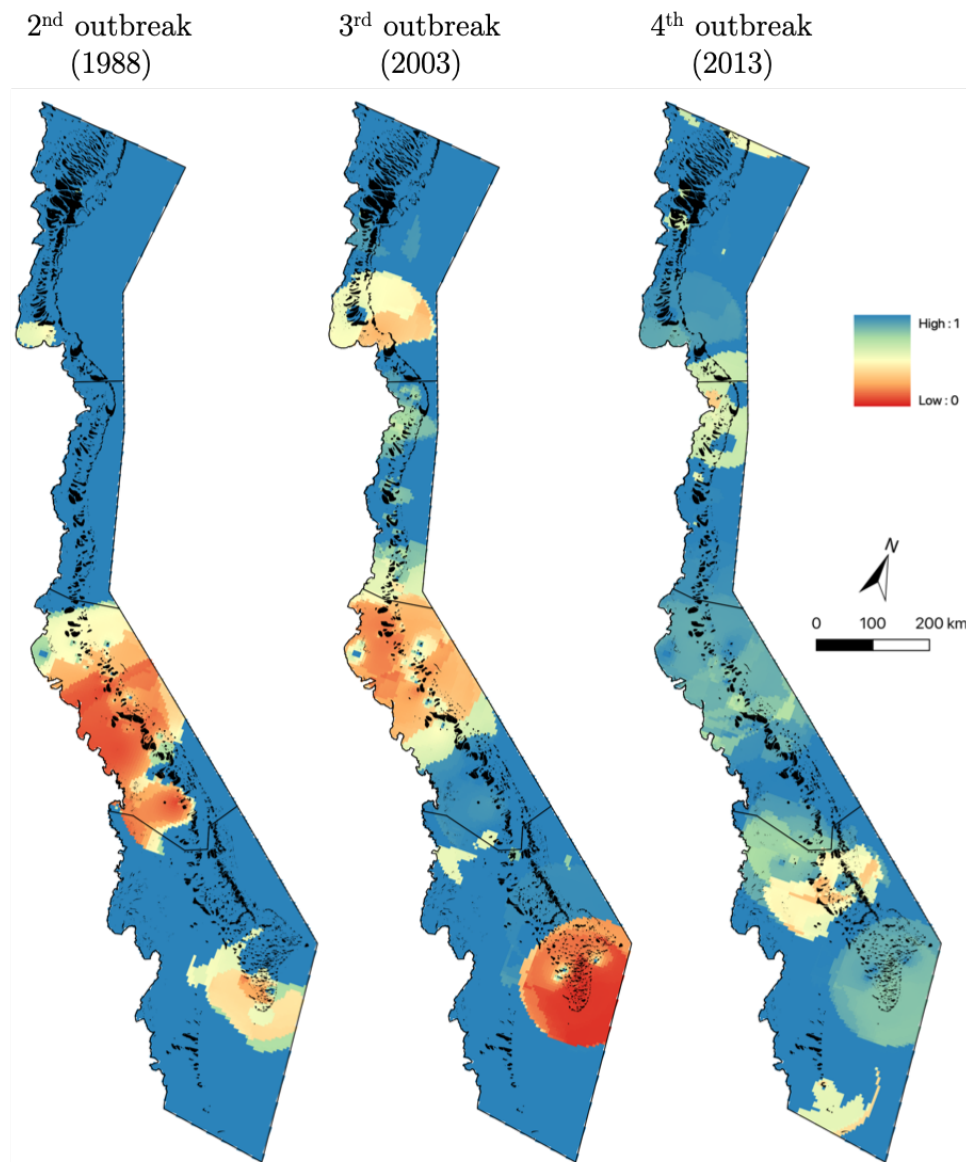
## M COTS initiation Box



Primary COTS outbreaks tend to occur on mid-shelf reefs in the north-central (Wet Tropics) region of the GBR between Lizard Island (14.6°S) and Cairns (16.6°S). *Credit: Wooldridge & Brodie (2015).*



## N COTS outbreak episodes



Last 3 major COTS outbreak episodes in the GBR.



## **Deriving a habitat quality index to inform reef conservation in the Great Barrier Reef**

How to identify and quantify the main threats to coral reefs

Nicolas Deffense

### **RESUME**

The Great Barrier Reef, as the world's largest coral reef ecosystem, is an exceptional site of global importance. Unfortunately, after thousands of years of existence, this wonderful biodiversity place, which shelters no less than 600 coral species and 1600 fish species, is under severe threats.

The main threat is climate change. It induces a rise in seawater temperature which causes bleaching events. In addition, we are witnessing an increase in the frequency of destructive tropical cyclones. Human activities along the coasts bordering the GBR are also responsible for the degradation of this vast marine ecosystem. Agricultural activities discharge many pollutants into the ocean that degrade water quality. The many COTS outbreaks that ravage some reefs are also a significant concern to be considered.

The aim of this thesis is to develop indices to understand, identify and quantify the main threats. First, single-threat indices are developed for each of them. Those indices have been designed to provide an estimate of coral cover loss. Then, we combine them to obtain a global reef-level habitat quality index for the entire GBR. The contribution of each threat in the global index will be deduced from coral cover data.

The habitat quality index can be used to improve estimates of connectivity between reefs to obtain a closer-to-reality connectivity. Most of the indices presented in this thesis have the advantage of giving an annual indication of the impact of the threats. They therefore allow us to monitor the evolution of the state of the GBR. This could help decision-making, particularly for the creation of protected areas.

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