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Assessment of Tropical Cyclone Risk to Coral Reefs: Case Study for Australia

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Abstract: In this study, we attempt to expand tropical cyclone (TC) risk assessment methodology and build an understanding of TC risk to Australia's natural environment by focusing on coral reefs. TCs are natural hazards known to have the potential to bring destruction due to associated gale-force winds, torrential rain, and storm surge. The focus of TC risk assessment studies has commonly centred around impacts on human livelihoods and infrastructure exposed to TC events. In our earlier study, we created a framework for assessing multi-hazard TC risk to the Australian population and infrastructure at the Local Government Area level. This methodology is used in this study with coral reefs as the focus. TC hazard, exposure, and vulnerability indices were created from selected coral-related datasets to calculate an overall TC risk index for the Ningaloo Reef (NR) and the Great Barrier Reef (GBR) regions. The obtained results demonstrate that the northern NR and the southern GBR had the highest risk values within the study area; however, limitations in data quality have meant that results are estimates at best. The study has shown the potential benefits of such a TC risk assessment framework that can be improved upon, as coral data collection becomes more readily available.

Keywords: Tropical Cyclones; risk; corals; the Ningaloo Reef; The Great Barrier Reef; Australia

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1. Introduction

Tropical Cyclones (TCs) are severe weather phenomena which form over the warm ocean waters in the tropics. TCs are becoming increasingly recognised as multi-hazardous events: destructive winds, storm surge, and torrential rain associated with TCs present threats to at-risk populations, infrastructure, and the natural environment [1]. While the multi-hazard consideration of TC risk for populations and infrastructure in Australia has been investigated [2], assessment of TC risk to the country's natural environment requires further research.

The projected increase in the intensity of TCs as a result of climate change [3] poses a risk not only to land-based assets but to the natural environment, including coral reef systems [4–10]. Literature suggests TCs can be responsible for significant coral damage [4]. The effect of extreme waves and currents caused by high wind speeds can result in the displacement of reef sand, gravel, and rubble, leading to a large amount of coral loss [5,6]. The highly complex framework of existing reefs can be stripped away and deposited far from their substrates [5–8]. Coral bodies that survive are far more vulnerable and spend decades to centuries regenerating and rebuilding resilience [9]. Many recovering corals are further disrupted by subsequent TCs, local man-made threats, and the rising risk of thermal stress from the ocean's warming, as well as its acidification [10].

Corals are keystone species of the reef ecosystem, meaning that coral-related stressors can create cascading effects for reef-associated organisms: cumulatively increasing the risk to mortality and risk of overall alterations to the biological and ecological function of reef systems [7,11,12]. Under anthropogenic climate change, reef systems may not be able to restore resilience before another stressor damages them, and this may lead to the disappearance of affected reefs [4,13]. This, in turn, will have further impacts on coastal protection from TCs [14]. Furthermore, the damage and disappearance of one coral reef could have flow-on effects for species that have ecological links to that area [4].

Globally, hundreds of millions of people from coastal communities rely heavily on coral reef resources that are vulnerable to both local and global changes in climate [15–18]. For example, coral reef systems supply one out of four fish caught in developing countries [10]. Even though our study focuses on Australia, this proof-of-concept methodology has the potential to be expanded to similar and surrounding Pacific Island Countries. Australia gains several economic and social benefits from coral reefs via tourism, fishing, recreational activities, and the direct and indirect employment of services related to these sectors. The Great Barrier Reef (GBR) has a total economic, social and icon asset value of AUD 56 billion, a national economic contribution of AUD 6.4 billion, and supports 64,000 jobs [19]. The Ningaloo Reef (NR) contributes AUD 110 million to the West Australian economy and over 1,000 direct and indirect full-time jobs associated with the reef [19]. Coral reef structure also provides physical protection for coastal environments and infrastructure from storm damage, erosion, and flooding via wind action [12,16,20], making it a Disaster Risk Reduction asset as well. Additionally, reefs also hold priceless cultural value for First Nations communities that have a deep-rooted and continuous connection to marine life that has been central to culture and lifestyle today and for 60,000 years beforehand [19]. Such cultural connections not only make reefs invaluable coastal assets but also provide a rich source of practical knowledge for TC risk mitigation [21]. Thus, the combined social, economic, and cultural importance of corals to reef systems and TC risk, in general, makes it a critical component of inclusion for this study.

Risk assessments aim to quantify and differentiate the risk of different regions or, in this case, sections of corals, based on contributing factors such as the expected hazard, exposure, and vulnerability. These risk assessments can go on to inform decision-makers aiming to improve Disaster Risk Reduction procedures and protect coral reef systems from TC hazards.

In this study, we assess and map TC risk to Australian coral reefs, considering coral exposure and vulnerability to TC hazards. Earlier studies have explored the effect TCs have on coral wellbeing by observations of past TC events, as well as through coral damage models [22,23]. However, these studies have not integrated the impacts TCs pose upon coral reef systems, along with information on coral exposure and vulnerability, to estimate regions with the highest risk in the future. Many coral reefs are World Heritage-listed sites and are also valuable economic, social, and cultural assets to populations in the region [14,23]. By estimating the risk to corals, information can be used to prioritise risk reduction efforts and sustain the benefits coral reefs provide to their communities and ecosystems. Corals were chosen for this risk assessment because TCs are one of the main causes of large-scale damage to corals [7,9] alongside marine heatwave/bleaching events. To the best of our knowledge, this is the first study to classify Australian coral reef systems as valuable assets, alongside human population and infrastructure on land, with a similar risk assessment methodology. The GBR and NR were chosen as study areas to discuss results and trends, as they are regions with high coral density and are UNESCO World Heritage-listed areas, globally acknowledged as important areas to be protected [24]. Compared to TC risk assessment of populations and infrastructure [2], coral data available is much more limited in detail and coverage. Thus, the results of this study represent the best estimates for TC risk to Australian corals based on currently available data.

2. Data and Methods

First, the study area is described in Section 2.1. For the selected study area, viable data indicators for each index of hazard, exposure, and vulnerability were sourced as described in Section 2.2. Geographic Information System (GIS) software, used to visualise spatial data and calculate risk components, is described in Section 2.3.

2.1. Study Area

This research assessed TC risk to Australian corals based on a global coral map shapefile from the United Nations Environment Programme (UNEP). With numerous coral reefs stretching across a large spatial extent, making it difficult to display with all features at sufficient scale, this study is focused on analyses of two study regions: the NR on the west coast and the southern GBR on the east coast of Australia. Their location, in context of Australia, is depicted in Figure 1.

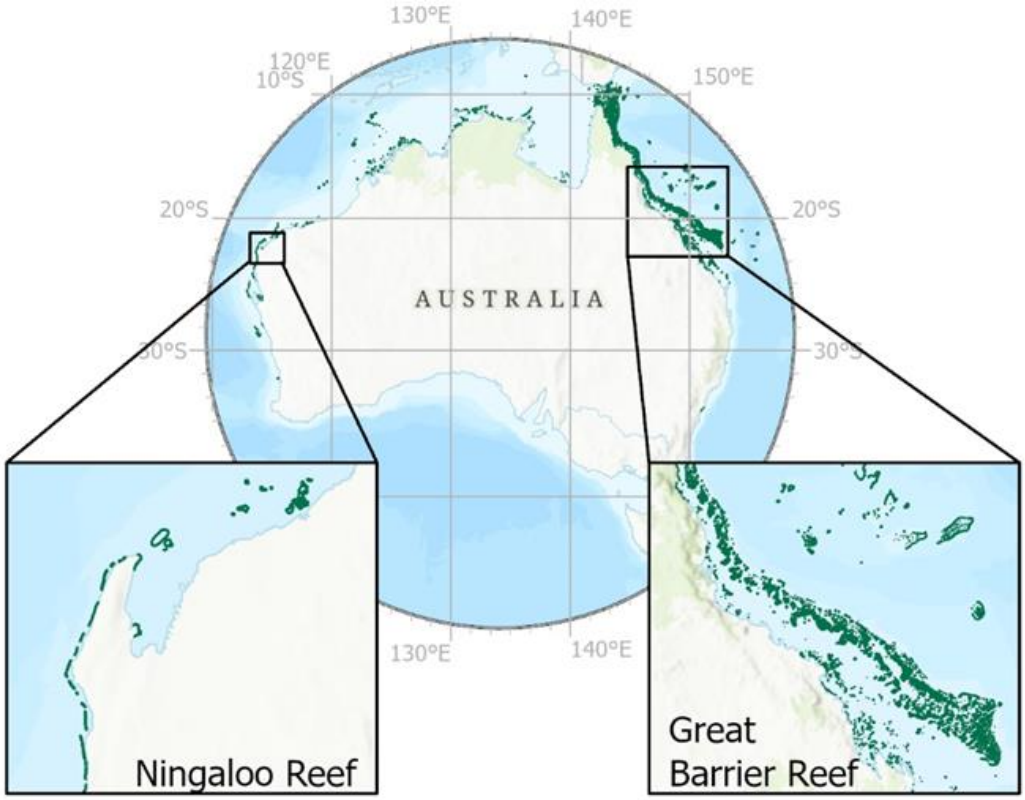


Figure 1. The Ningaloo Reef and the southern Great Barrier Reef study regions in context to Australia. Green polygons denote the location of corals in Australia included in this study.

The GBR is the world's largest coral reef system, stretching for over 2300 kilometres. It is composed of over 2900 individual reefs and 900 islands over an area of approximately 344,400 km^2. In 1981, the GBR was selected as a World Heritage Site. The NR that is also the World Heritage Site is 260 kilometres long. It is the largest fringing coral reef in Australia and the only large reef positioned very close to a landmass.

2.2. Definition of Risk

Risk is commonly defined as the product of its three components—hazard, exposure, and vulnerability [25,26]—with hazard described as the probability and intensity of the harmful event, exposure described as the valuable assets that are possibly lost, and vulnerability described as the susceptibility of exposed elements to be negatively impacted by the hazard. Using an indicator-based method, multiple data inputs for each component of risk are used to create indices of hazard, exposure, and vulnerability before calculating risk. In

the context of corals in this study, wind is the main TC-related hazard, as it causes damaging waves, while exposure can be represented by indicators that reveal how much or how valuable corals are in the region. Vulnerability indicators would, then, give characteristics of the corals that make it more or less impacted by damages.

2.3. Selection of Indicators

Hazard

Of the multi-hazard effects of TCs on Australia, as assessed in Do and Kuleshov [2], wind hazard was decided to be the only important hazard included in risk assessment to corals. Strong near-surface winds produced by TCs cause enhanced wave movement over the ocean, which are known to physically damage coral reefs and cause breakage. Flood and landslide hazards were not applicable, while storm surge, although known to cause strong wave movement that can also damage corals, had surge height data only along the coastline, making it unreliable to use further out to the ocean where water depth and storm surge interactions differ. High resolution wind hazard data were sourced from Arthur (2018) [27], measuring the 100-year average return interval of 0.2 second wind gusts 10 m from the surface. This faster wind speed layer had its values joined to the coral dataset, taking the average wind gust speed over each polygon it overlapped.

Exposure

Although the coral data indicate, broadly, the locations of corals, they fail to indicate the density or value of corals within those polygons. Rather than assuming that the corals are uniformly distributed throughout each polygon, the density of corals can be approximated based upon other environmental factors. The two key indicators for estimating coral density, and thus exposure, are proxies of biodiversity and rugosity (structural complexity).

The biodiversity of corals is important, as it can be indicative of the value of coral areas. It is assumed, here, that more biodiverse patches of corals are more important and valuable than patches with lower biodiversity. In this study, biodiversity was derived from the number of coral species within 880 km $\times$ 880 km grids [28]. As only this low resolution dataset for biodiversity was available, rather than distinguishing biodiversity between each coral polygon, sections of the larger reef were categorised with the same biodiversity value. While higher resolution is sought after and should be improved upon in future work, the inclusion of biodiversity as an exposure indicator is deemed important and relevant to TC risk to corals.

Rugosity is used in marine and coral biology to measure the complexity of a substrate by measuring how far a chain of equal length travels across a straight line transect or by other techniques on a larger scale, such as remote sensing [29]. It has been found to correlate with higher coral reef fish diversity, and remote sensing is currently being used to measure rugosity across reefs at greater scales than those previously restricted to the path of scanning ships [29]. Coral cover also tends to positively accompany habitats with greater structural complexity, as they use the substrate to aggregate and build the foundation of the reef systems [30]. Higher rugosity enables higher biodiversity with more structures and microenvironments for different corals to live in, as well as indicates the likelihood of colonisation and recovery after disturbance events [31]. In this study, rugosity was estimated by taking the standard deviation of bathymetry data in each section of corals. This resulted in an estimated variation of coral height, where a higher value suggested a greater number of coral bed heights and, thus, more complex environments. Although other studies have used different methods, such as modelling rugosity, as surface area from bathymetry data [32,33], the approach taken in this study allowed for low computational costs across large datasets for the whole country.

Vulnerability

Depth of the seafloor, otherwise known as bathymetry, is a helpful indicator of coral vulnerability, as depth can provide protection against the waves and turbulence that TC winds produce [5,7]. Earlier studies demonstrated correlations between coral species, richness, and depth, as well as what exposes them to waves [34]. It was found, in Scoffin

(1993) [5], that corals at depths of 20 m can be broken or detached by 5–15 m (with the possibility of 20 m) waves that are generated by TCs, with branching colonies being more susceptible to damage than larger, upright structures. This suggested that the shallower the corals, the more vulnerable they are, which can increase the chance of damage or removal. Bathymetry data were sourced from the General Bathymetric Chart of the Oceans (GEBCO) [35], with a resolution of 15 arc-seconds, a 450 m × 450 m grid.

Local integrated threats created directly from humans contribute to 60% of the world's damage made to coral reefs [10], and they impact how the coral recovers and builds resilience. The local integrated threats included in this assessment are overfishing and destructive fishing, coastal development, watershed-based pollution, and marine-based pollution. Overfishing and destruction are pervasive, and over 55% of the world's reefs are affected by them, due to unsustainable harvesting and using explosives or poisons without correct assessment and consideration of the environment [10]. Coastal development for the greater good of our society can impact marine systems if not sustainably managed. Unsustainable tourism, coastal engineering and construction, and landfilling with their expected runoff, as well as sewage discharge, threaten 25% of the world's reefs [10]. Additionally, watershed-based pollution from agricultural practices also affects 25% of reefs. Among reefs, 10% are impacted by marine-based pollution from toxins that ships and marine vessels produce, mining, and anchors and grounding causing physical damage. These local integrated threats were compiled and classified by the United Nations Environmental Programme (UNEP) in their Reefs at Risk Revisited global analysis [10], which came at a 500 m resolution.

Thermal stress on coral reefs originates from the warming sea surface temperatures due to both natural climate variability (e.g., El Niño-Southern Oscillation) and anthropogenic climate change, which is projected to continue to increase into the future [36], likely because of the oceans absorbing over 90% of the excess energy trapped by increased greenhouse gas emissions [37,38]. If sea surface temperatures remain abnormally warmer than average for a prolonged period, a marine heatwave occurs, which can have detrimental bleaching effects on coral reefs [39]. Coral bleaching has a severe impact on marine ecosystems. Corals rely on a symbiotic relationship with zooxanthellae (a single-celled organism that lives within coral) to have optimum productivity. Without this relationship, coral struggle to survive [40], as increased sea surface temperatures cause zooxanthellae to be expelled from the coral, disrupting this relationship and, thus, depressing coral growth, and increasing mortality [41]. Reefs are also at risk, as continuous bleaching impacts could reduce rugosity and, therefore, have a chain of impact through to biodiversity and recovery [42]. The amount of thermal stress exerted on a region increases the vulnerability of corals and increases impacts they would face if TCs were to occur. Thermal stress data were similarly taken from UNEP's Reefs at Risk Revisited dataset [10].

Ocean acidification occurs because of the increased uptake of carbon dioxide from the atmosphere, in turn, decreasing the pH level of the ocean. With the oceans being more acidic, it makes it more challenging for corals, as marine calcifying organisms, to grow, repair, and function [43]. In addition to being impacted by other disturbances such as TCs, local threat, and coral bleaching, this reduction in calcification could heavily impact the recovery and resilience of corals, leaving them vulnerable for longer. Higher ocean acidification indicates higher vulnerability of corals in the event of a TC and was, thus, included in the vulnerability index. Data were also sourced from UNEP's Reefs at Risk Revisited dataset [10].

The data that were used to create the risk maps are summarised in Table 1.

Table 1. Data for TC coral risk assessment. Links are provided for the data sources as well as the year that the dataset was last updated.

Indicator	Dataset Used	Source	Year
	Hazard		
Wind hazard	Raster Cyclone wind, 100yr return period	Geosciences Australia [27]	2018
	Exposure		
Biodiversity	Global patterns of marine biodiversity (species richness) across 13 major species groups	UNEP-WCMC [28]	2010
Rugosity	Calculated as Standard deviation of bathymetry within that coral region	GEBCO [35]	2019
	Vulnerability		
Depth	Sea floor depth from bathymetry data	GEBCO [35]	2019
Local Integrated Threat	Threats from a wide range of human activities	UNEP Reefs at risk [10]	2011
Thermal Stress	Past and Projected Thermal Stress on Coral Reefs	UNEP Reefs at risk [10]	2011
Ocean Acidification	Past and Projected Ocean Acidification on Coral Reefs	UNEP Reefs at risk [10]	2011
	Shape layers		
Global Coral Map	Shapefile containing the distribution of Coral reefs	UNEP-WCMC [44]	2010

2.4. Methodology for Assessment of TC Risk to Corals

The indicator-based risk assessment methodology used in this study applies the same framework developed in an earlier study on multi-hazard TC risk assessment for Australia [2]. Where that study compares TC risk across Local Government Areas, this study uses new, coral-specific datasets to compare TC coral risk across each cluster or polygon of corals, as denoted by data on the distribution of coral reefs from the UNEP World Conservation Monitoring Centre [44].

Risk is calculated as the product of hazard, exposure, and vulnerability indices [26], as presented by Equation (1):

$$\text{Risk} = \text{Hazard} \times \text{Exposure} \times \text{Vulnerability} \quad (1)$$

Higher values in either component increases risk, and without either component, risk is negligible. This is because a hazard must be present to an exposed asset that is vulnerable or susceptible to negative impacts for there to be a risk.

The diagram in Figure 2 visualises the relationship and process from the indicator level (3) to index (2) and risk (1) levels. Starting from indicator data (3), categorised as components of either hazard, exposure, or vulnerability, data are standardised and combined to create hazard, exposure, and vulnerability indices at level (2). Finally, risk is calculated as the product of each index with equation 1. Indicator data were standardised into a 0 to 1 range using decile normalisation. Equal weighting was used to calculate the exposure index from biodiversity and rugosity indicators, while Pareto ranking was used in the vulnerability index. More information on the use of decile normalisation, equal weighting, and Pareto ranking can be found in [2].

Geographical Information Systems (GIS) software, ArcGIS Pro, was used in tandem with Python scripts to prepare, clean and rank data before calculating risk components and final estimated risk. Processes are described in the diagram shown in Figure 3. Once all data had been added, normalised, and calculated, all layers were mapped, with five classes, using Natural Breaks symbolisation.

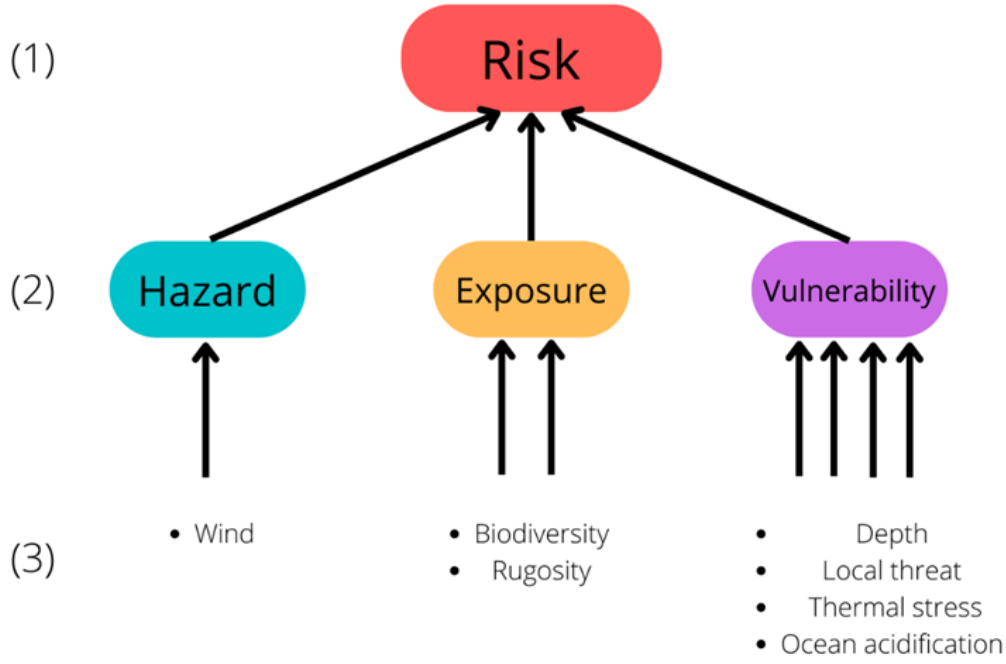


Figure 2. Risk index flowchart from indicator level (3) to index (2) and risk (1) levels. Each indicator is listed in level 3 grouped depending on the categorisation under either hazard, exposure, or vulnerability indices.

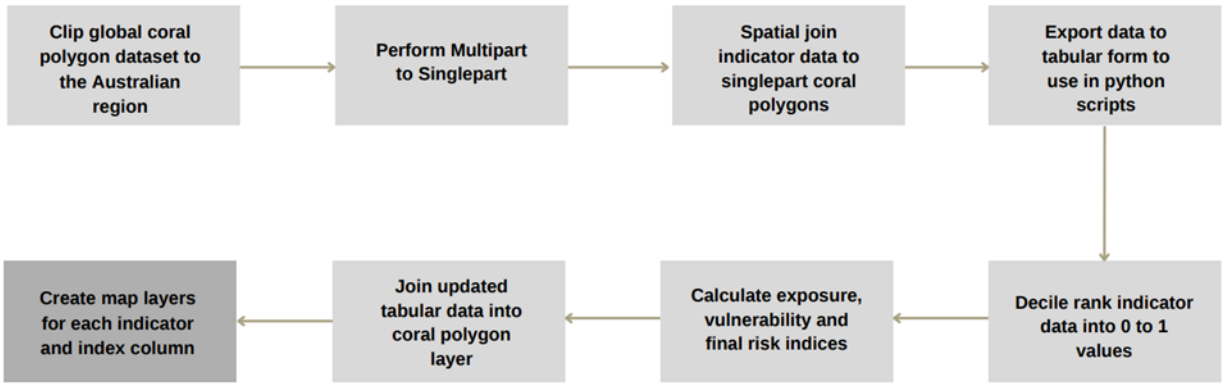


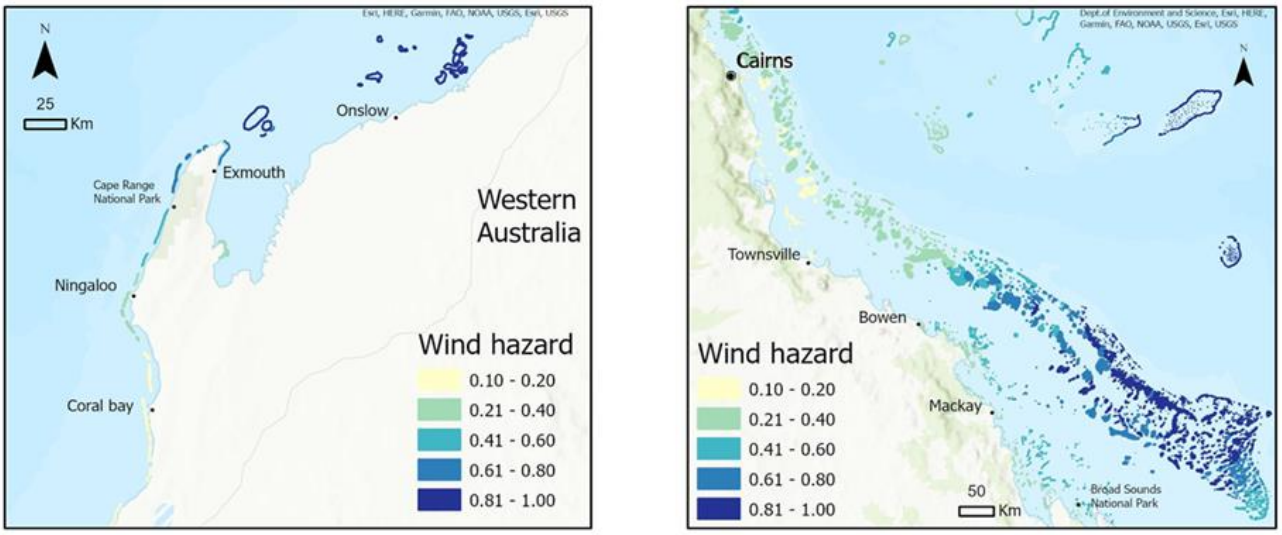
Figure 3. Outline of GIS and Python processes used to create a coral-mapped risk index from raw data.

3. Results and Discussion

The results presented and discussed in this section are focused on two study regions from the NR on the west coast and the southern GBR on the east coast of Australia (Figure 1).

3.1. Hazard

Wind hazard at NR (Figure 4a) shows a clear trend starting from the very low hazard at the southmost polygon of the map extent, increasing northwards, in hazard, to low (0.21–0.40) offshore Ningaloo, medium (0.41–0.60) and high (0.61–0.80) at Cape Range National Park, and from offshore Exmouth northwards to very high wind hazard. The GBR extent shows a similar pattern, however, with hazards increasing southwards (Figure 4b). The hazard increases southward to medium and high, simultaneously, from offshore Bowen, and very high hazard is then occurring in polygons amongst medium and high hazards from around offshore Mackay.



(**a**) (**b**)

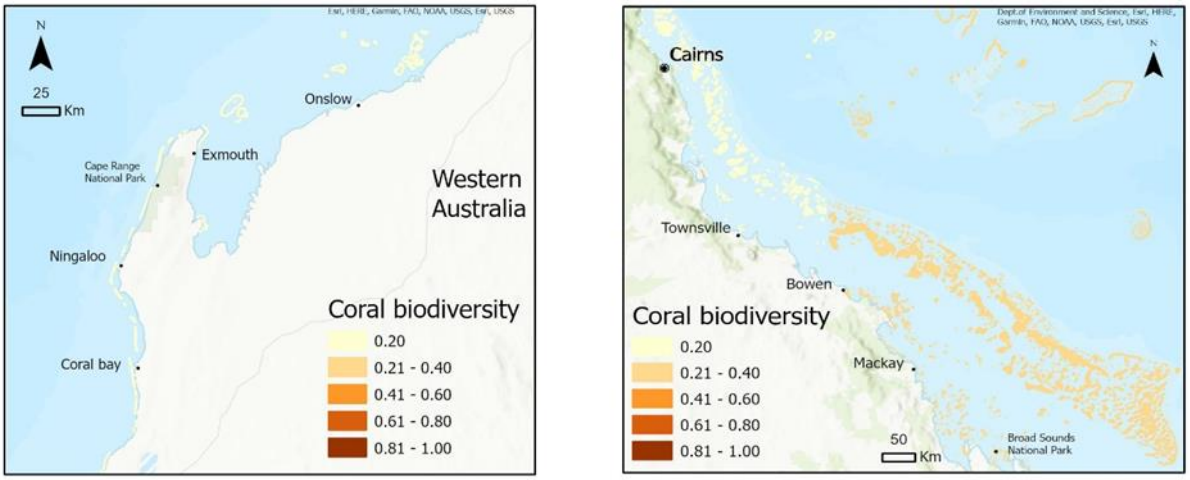
Figure 4. Tropical Cyclone wind hazard to corals in the Ningaloo Reef (**a**) and the southern Great Barrier Reef (**b**). Higher (darker) values denote higher 0.2 sec cyclonic wind gusts modelled for the 100-year return period.

These two trends, although they look opposite to each other, can be explained by how TC strength and intensity increases as it travels away from the equator until its further development becomes limited by cooler sea surface temperatures [45]. In this case, a stronger TC wind hazard is found towards the region above the NR extent, while winds seem to peak around the latitude of Mackay in the GBR extent. Although this wind hazard indicator is mapped to the extent of corals, it does not necessarily mean corals with high wind hazard values will experience the most damage. Exposure and vulnerability indices are combined with the hazard indicator to determine impacts in the risk index.

3.2. Exposure

All NR exposure polygons are classed at lowest biodiversity, as seen in Figure 5a. The northwest region of the GBR map (Figure 5b) displays the same lowest biodiversity that the NR has; however, it also has a higher value of biodiversity (0.21–0.40) from offshore Bowen southwards. A majority of the coral polygons over 100 km offshore in the northeast also have 0.21–0.40 values.

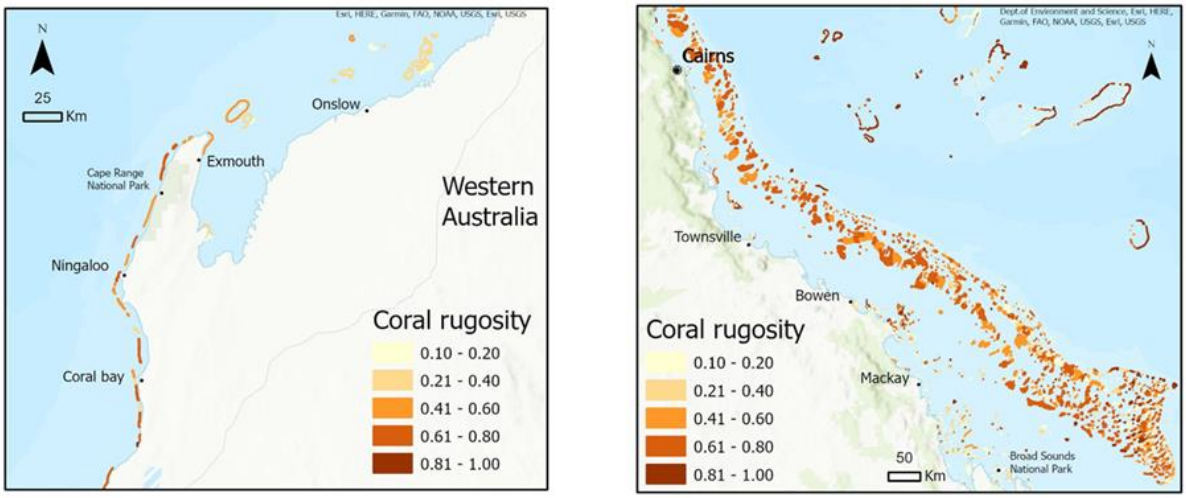
The trend seen in Figure 5b at the GBR shows that biodiversity is very similar for large spatial regions. This could be explained by the low resolution of input data for the biodiversity indicator. The literature suggests latitude can be a predictor of marine biodiversity [28]; however, results suggest, at least for coral reef systems along the coast, there must be other factors at play, as the NR shares the same latitude as the lower section of the GBR. Being known as one of the most famous and colourful reef systems in the world, it would be expected that the GBR would have much higher biodiversity values than 0.20–0.40. Upon further inspection of the input data, these lower values arise as a result of corals along the northern coastline, outside the focus NR and GBR areas, having comparatively higher values. Rather than a limitation, this just means that selected focus regions are less exposed than Australia's more northern corals. The limitation of low resolution input data, however, suggests that, in reality, there is more variation in biodiversity within similar valued sections than presented.



(**a**) (**b**)

Figure 5. Exposure indicator maps of coral biodiversity in the Ningaloo Reef (**a**) and the southern Great Barrier Reef (**b**). Higher (darker) values denote a higher number of coral species.

NR coral rugosity presented in Figure 6a varied across each coral segment. The highest of rugosity values were found at offshore Coral Bay, and the lowest values were south of Exmouth and northeast of Onslow. The GBR rugosity (Figure 6b), similar to Ningaloo, had varying values and showcased regions from lowest to highest rugosity values. There is quite a large amount of very high rugosity around the Whitsunday Islands (between Bowen and Mackay), and high rugosity is seen in both inner and outer reefs, with the far outer reefs in the northeast holding the highest values.



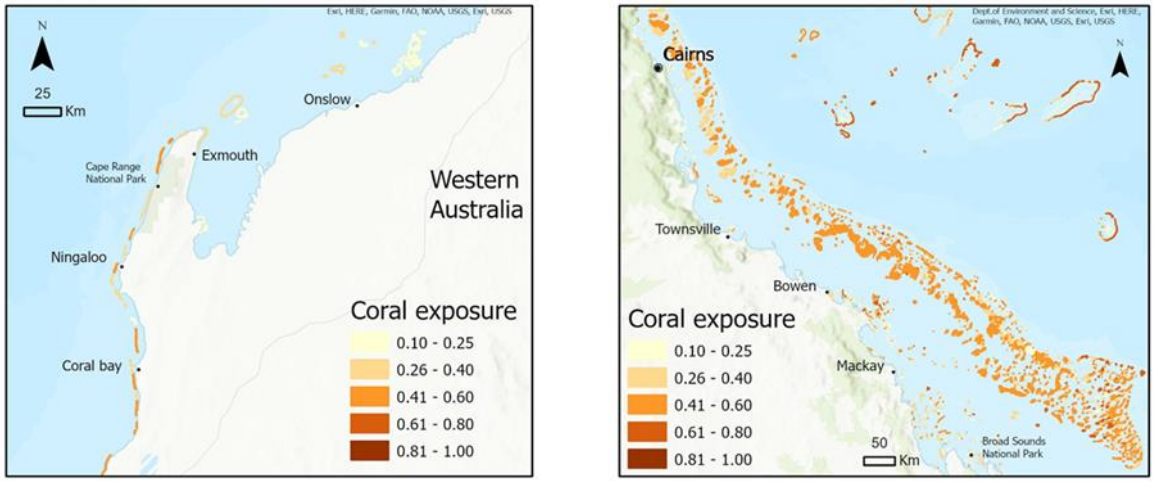
(**a**) (**b**)

Figure 6. Exposure indicator maps of coral rugosity in the Ningaloo Reef (**a**) and the southern Great Barrier Reef (**b**). Higher (darker) values denote higher rugosity of coral reefs.

This study used high-resolution bathymetry data and calculated the rugosity from standard deviation as a proxy of how much the depth varied within the polygon. This value was influenced by the lowest and highest points of depth within each polygon. There was no ability to look at the data spatially to find where points were or to know how the polygon surface of the reef varied between those two points; for example, it could have been a flat textured slope or a very bumpy textured fluctuating incline. Due to this methodology, larger polygons would, therefore, be more likely to have a high rugosity

value, as there are more data points to widen the distribution. This can explain highest values of 0.81–1.00 being found in outer northeast reef polygons where they are mapped as single long lines of corals, rather than smaller ovular shaped polygons commonly found in the main reef. Apart from these longer polygons, no evident trend is found for rugosity, and we can assume that similarly sized coral polygons can have their exposure compared by their given rugosity value.

The equally weighted exposure index for the NR in Figure 7a ranges from very low to medium (0.10–0.60) exposure for most coral polygons. Higher value corals are found along the western coastline from Coral Bay to Exmouth, and lowest values are seen northeast of Onslow. The GBR exposure index (Figure 7b) shows very similar medium values for most of the main reef. Higher exposure is found in both the southeast reef offshore from the Broad Sounds National Park and the far outer reefs in the northeast. The exposure between Townsville and Mackay is mostly medium exposure, and a large portion of the low exposure is found in the reef polygons that are situated northwest and close to Cairns.



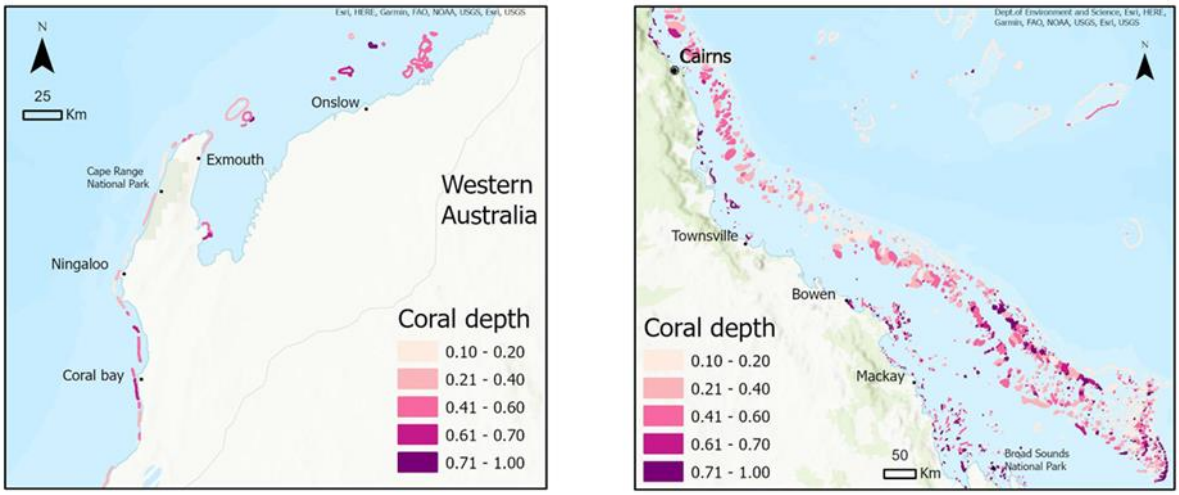
(**a**) (**b**)

Figure 7. Coral exposure index maps are calculated by equally weighting the two exposure indicators for the Ningaloo Reef (**a**) and the southern Great Barrier Reef (**b**). Higher (darker) values denote higher exposure.

The exposure index shows the combination of both biodiversity and rugosity. As expected, rugosity trends dominated the exposure index in the NR, as biodiversity values were universal across the map extent. The high exposure polygons found in the south reef and far outer reefs of the GBR are representative of the high rugosity they possess, as well as the increase in biodiversity compared to northern reefs and the NR. As a result, the produced exposure index suggests these corals with highest values to be most exposed when compared against other corals in the dataset.

3.3. Vulnerability

NR coral depth (Figure 8a) exhibited a full range of very low to very high coral depth values across the map extent. There are higher values, and thus, shallower depths are found offshore from Onslow and offshore east of Exmouth, as well as surrounding Coral Bay. In the GBR(Figure 8b), the majority of the very high value polygons are situated in the southeast area of the map, extending from Bowen southwards. Many polygons within 50 km of the shoreline have high to very high values. The far outer reefs in the north have much lower values and, thus, are associated with corals deeper along the sea floor.



(**a**) (**b**)

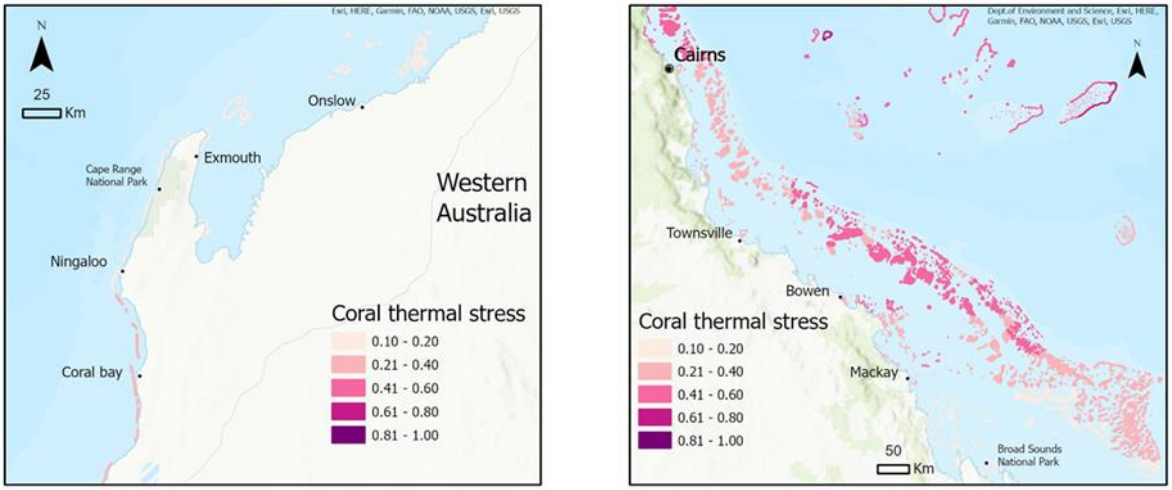
Figure 8. Vulnerability indicator maps of coral depth in the Ningaloo Reef (**a**) and the southern Great Barrier Reef (**b**). Higher (darker) values denote shallower depths at which corals are found.

While corals are commonly found in the first 20 m below sea level [5], there is still a difference in coral depth within that zone. Highest coral depth vulnerability values of 0.71–1.00 represent corals in the first few metres below sea level, while the lowest class (0.10–0.20) represent corals over 20 m below sea level. High resolution bathymetry data used in this indicator allowed for accurate comparisons; however, the high resolution also meant the depth value had to be summarised, as multiple cells commonly overlapped coral polygons. Thus, the median depth was used to try to best capture the depth at which corals exist for most of the polygon. Many coral polygons were found to be very shallow and, therefore, vulnerable within 50 km of the coastline, which is to be expected as the seafloor depth commonly decreases towards land boundaries such as beaches. This vulnerability indicator of coral depth contributes to our understanding of the physical vulnerability of corals and shows the corals most likely to take the most damage if TC events were to occur.

Figure 9a shows that the NR corals have mostly very low to low thermal stress vulnerability. Northward of Ningaloo has a very low vulnerability, and travelling Southward from Ningaloo the thermal stress increases to low vulnerability (0.21–0.40) polygons. The GBR showed more variation and higher thermal stress values (Figure 9b). There seems to be a segmented pattern across the map, with very low vulnerability around Broad Sounds National Park. Medium thermal stress (0.41–0.60) is mostly seen between Townsville and Mackay in reefs within 150 km of the coastline. Similar medium values are found above Cairns, while some high thermal vulnerability corals are found amongst the outer northern reefs.

The thermal stress, whilst still low overall in Figure 9a, shows southwards polygons of the NR are slightly more vulnerable than those northward. Coral bleaching has occurred in WA during past La Niña events, with the 2010–2011 event being the first recorded warm water bleaching for multiple sites along the coast [46], as warmer water accumulates in the Western Pacific and is carried by the throughflow down the WA coast [47]. The World Heritage Outlook has reflected that the reef missed the major bleaching event in 2016 [48]; however, concerns for future bleaching events and the large impact they could have are high [49]. The low vulnerability shown could be reflective of the smaller amount of recorded bleaching events, as well as the resilience the coral reefs have built up since missing the bleaching event in 2016. In comparison, the GBR has faced intense coral bleaching events in the last 20 years [46,50]. The GBR is also more susceptible to El Niño years, given less cloud coverage combined with abnormally warm sea surface temperatures [51]. Figure 9b's larger proportion of medium to high thermal stress values in the GBR compared to Ningaloo

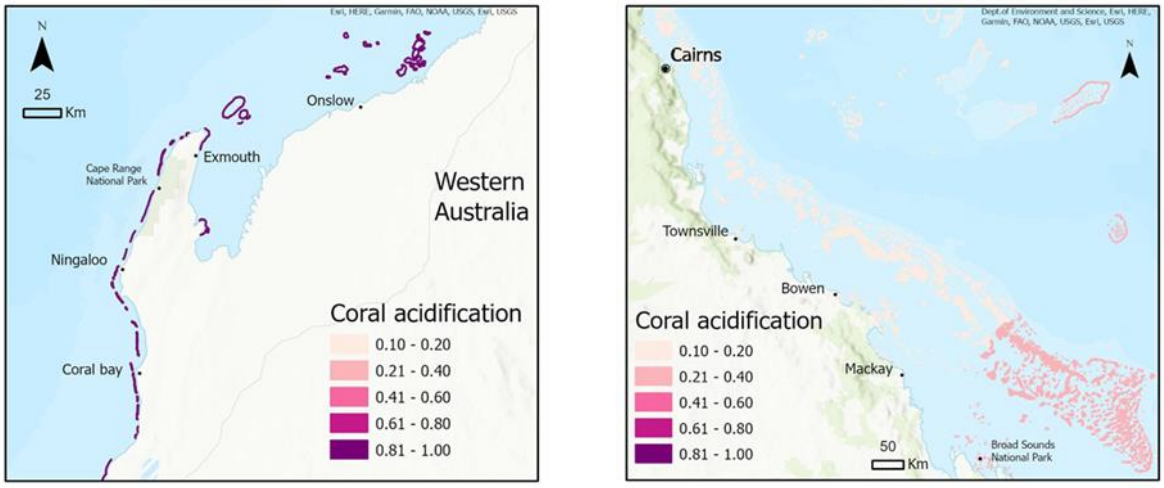
supports records that the GBR has experienced more recent damage and, therefore, will be more vulnerable than Ningaloo to the next bleaching event due to thermal stress.



(**a**) (**b**)

Figure 9. Vulnerability indicator maps of coral thermal stress in the Ningaloo Reef (**a**) and the southern Great Barrier Reef (**b**). Higher (darker) values denote greater thermal stress to corals.

Figure 10a shows that all the NR corals have very high coral acidification values. In contrast, the GBR exhibits low coral acidification vulnerability (0.21–0.40) in the southeast, with vulnerability reducing to very low from offshore Mackay northwards (Figure 10b). Only the two far outer eastern reef systems are a similar low value, while the remainder are very low.



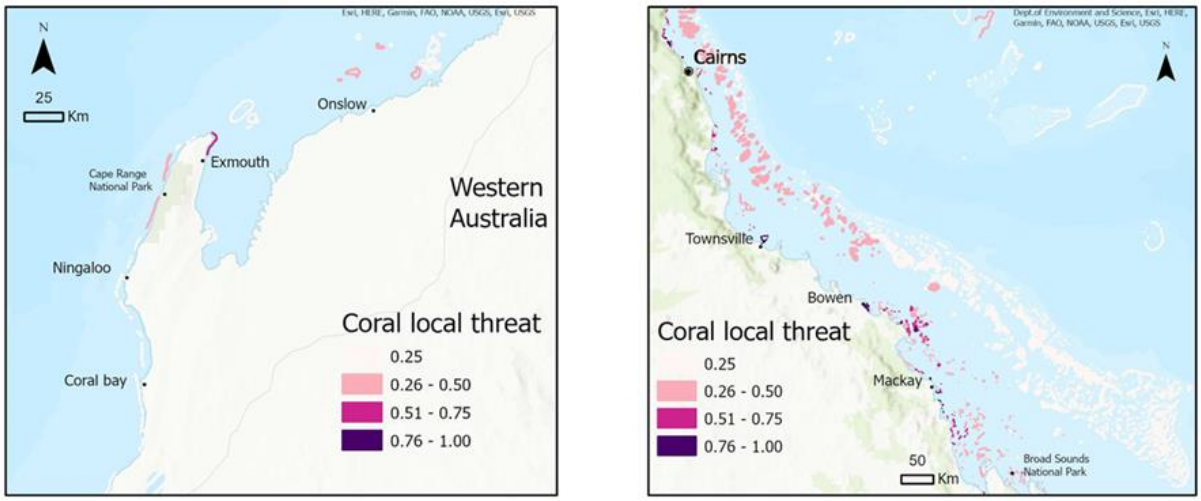
(**a**) (**b**)

Figure 10. Vulnerability indicator maps of coral acidification in the Ningaloo Reef (**a**) and the southern Great Barrier Reef (**b**). Higher (darker) values denote greater coral acidification.

Shallow ocean waters commonly possess high saturations of aragonite, the form of calcium that corals and other calcifying organisms process to form their skeletons [52], but these saturation levels are expected to decline [53]. Given there are polygons in the map extent of the GBR that are of a lower latitude than the Ningaloo polygons, they could be a factor of there being the potential difference in aragonite levels and, hence, vulnerability. This could be supported by the increase in vulnerability further south shown in Figure 10b.

However, the Ningaloo polygons are approximately within the same latitude as southern polygons of the GBR, but they are of a very high vulnerability (Figure 10a). The World Heritage Outlook Report [54] states that the NR's overall conservation outlook is "good with some concern". Coral reefs are at a high threat of future acidification events [55]; however, the report for the GBR [50] outlines that the conservation outlook is at critical risk, with no mention of coral acidification. More research into both natural and anthropogenic variables will be needed to explain the difference found in this assessment.

The local threat in the NR in Figure 11a is mostly very low, with the highest threatened polygon being just offshore of Exmouth. Medium–low threat value corals are situated off Cape Range National Park and Onslow. The local threat vulnerability of the GBR is very low for most of the polygons further offshore of Bowen and southwards (Figure 11b). North of Bowen, the majority of the polygons are at low vulnerability (0.26–0.50). The far outer reef beyond 100 km is all very low vulnerability, except for one polygon at the northmost edge of the figure being low. The polygons with vulnerability at medium to very high all reside within 50 km along the coast of QLD from offshore Cairns to Mackay.

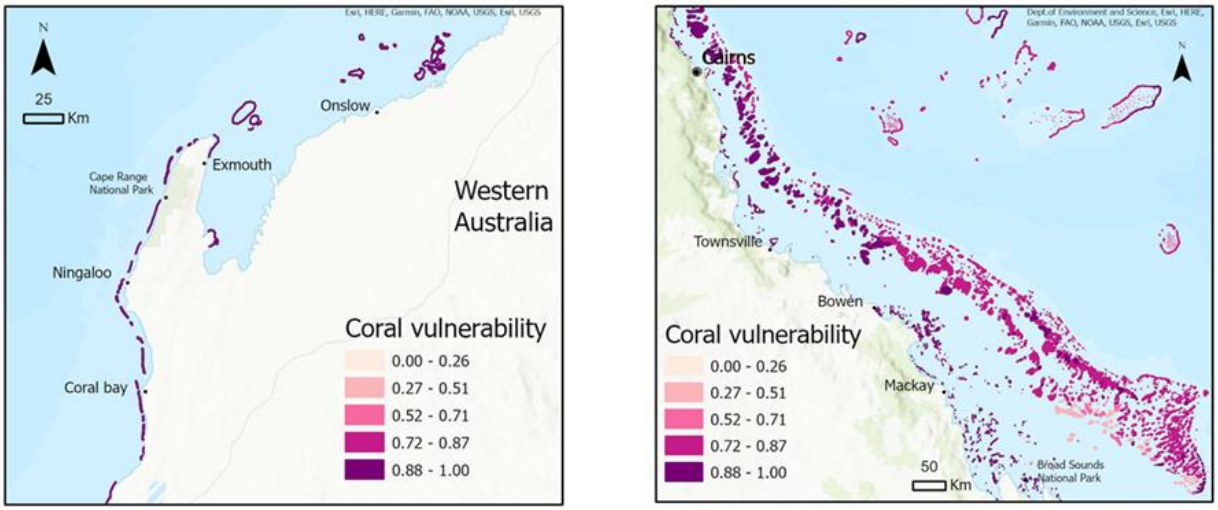


(**a**) (**b**)

Figure 11. Vulnerability indicator maps of coral local threat in the Ningaloo Reef (**a**) and the southern Great Barrier Reef (**b**). Higher (darker) values denote greater local threat to corals.

A large number of polygons with high vulnerability close to shore in the GBR is to be expected from the results, given the closer exposure to all four contributing factors (overfishing, development, as well as watershed and marine pollution). For the NR, Exmouth is the largest town on the map extent, and it has a large fishing and tourism presence. Similarly, at the GBR, communities such as Mackay, Bowen, and Townsville interact with the ocean from a recreational lens, are likely to have ongoing coastal development, and also have various waterways that interact with agricultural land and flow out into the ocean. Thus, this local threat indicator gives a good indication of included threats to corals at a high resolution, and it is used, in this study, to inform the vulnerability index.

The total coral vulnerability index for the NR displays all coral polygons within the map extent as having very high coral vulnerability (Figure 12a). The GBR, however, varies from polygons with low to very high vulnerability. Large areas of very high vulnerability are shown in Figure 12b, around offshore Townsville and Cairns, in the northwest region of the map extent. Reefs from offshore Bowen southwards decrease in vulnerability but still show high and medium hazard areas of abundance, and there are still very high vulnerability polygons amongst them.



(**a**) (**b**)

Figure 12. Coral vulnerability index maps calculated by Pareto ranking the four vulnerability indicators (depth, thermal stress, acidification, local threat) for the Ningaloo Reef (**a**) and the southern Great Barrier Reef (**b**). Higher (darker) values denote higher vulnerability of corals.

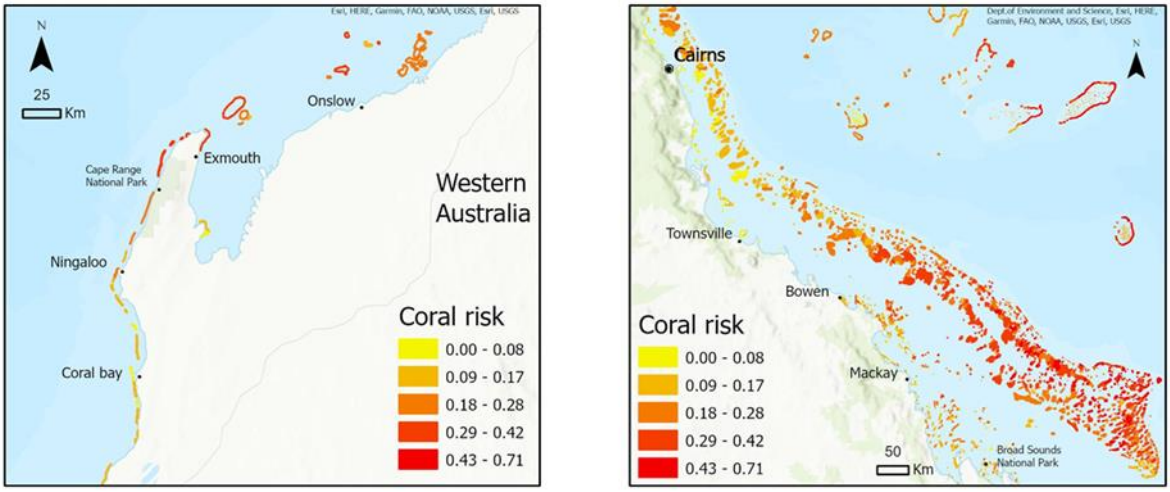
The coral vulnerability index has summarised polygons' vulnerabilities, taking into account the most extreme values across all four vulnerabilities using Pareto ranking. This could partially explain the NR possessing all very high polygons because of the extreme vulnerability to ocean acidification. The GBR also has a high number of polygons that exhibit very high index values from their extreme vulnerability to one indicator or accumulation of extreme vulnerability of multiple indicators. In both study regions, there are few very low index values and only a small number of low and medium vulnerability, with the majority of the polygons being high or very high vulnerability. This emphasises the urgency for not only disaster management but also sustainable marine management and conservation to prepare, protect, and repair the reefs' resilience from these global and local disturbances.

3.4. Tropical Cyclone Risk to Corals

Figure 13a shows that the overall TC risk to corals for the NG is very low in the southern half of the map extent. The very high TC risk to corals can be observed offshore of Cape Range National Park, Exmouth, and Onslow. The northern half of the map extent exhibits mostly medium–very high risk. The GBR exhibits very low risk and low risk to corals around the northern half of the map extent, and the risk increases in the polygons in the southern half (Figure 13b). Very high and high polygons dominate the southeast main reef, while easternmost outer reefs also exhibit high risk. Despite this general trend of higher risk in the south and east of the reef, there is still variation between closer coral polygons, especially with medium to low values just off the coast of Mackay and Broad Sounds National Park.

The product of the wind hazard, exposure, and vulnerability indices exhibits the overall TC risk to corals of the NR and the GBR. The very high polygons around Exmouth are an accumulation of risk from high vulnerability, as well as high wind hazard and some points of high exposure, due to rugosity and biodiversity. This is similar to the GBR, with a large number of very high-risk polygons in the southeast region of the map extent. This novel assessment shows that, from observation, a large area of corals is at medium to very high risk to TCs. As corals are important ecological and economic assets, negative impacts to them are expected to have flow-on effects into related industries. The results of these risk maps have identified corals most at risk to TCs, and they support the need for corals to

be included in natural disaster risk reduction strategies alongside protecting human lives and infrastructure.



(**a**) (**b**)

Figure 13. Tropical Cyclone risk to corals in the Ningaloo Reef (**a**) and the southern Great Barrier Reef (**b**). Higher (red) values denote higher risk.

3.5. Limitations

Many coral polygons were calculated with the same values for biodiversity due to the larger resolution of the data. If there was a variation of biodiversity of corals between neighbouring polygons, it was impossible, with the current data, to distinguish that. There is also a chance of duplicity in rugosity and biodiversity, as the two variables have been found, in previous studies, to be positively correlated [29]. These limitations could be improved once high-resolution continuous biodiversity data for coral reefs becomes available.

Rugosity methodology also had its limitations due to the choice of calculation as standard deviation, which gave an overview of the difference in depth; however, no other values of how the surface area of each polygon differed across the plane. The bathymetry data were chosen, as it was universal across Australia to calculate rugosity. However, for more accuracy, continuous Australia-wide rugosity data that measures the structural complexity of each polygon is required. This kind of data was not able to be found Australia-wide. An alternative approach to rugosity could be a slope-derived calculation that considers the change in bathymetry between surrounding values. Some high-resolution rugosity datasets exist from scanning ship tracks that lack the national coverage; however, machine learning could be used to estimate rugosity values across the larger bathymetry database based upon the few regions that have been scanned in high detail.

Another limitation with coral depth vulnerability was the research into which corals at what depth are most vulnerable to TCs. Corals that are in shallower water are exposed to far more wind action and intensity; however, earlier studies have found that shallower coral could be more acclimatized to this and that corals at "middle depth" are exposed to intense wave action but less frequently [5]. For simplicity, this study chose a linear approach, assuming that shallower coral is more vulnerable. Further research could explore the possibility of integrating a vulnerability layer associated with potential coral acclimation to wind action.

An overall limitation in searching for coral data was the lack of continuous data across Australia. This was because large amounts of ecological data are collected via in-person fieldwork. In recent years, remote sensing technology has been able to capture more and more ecological-based information that will be essential to future conservation efforts [56].

Coral data that can validate risk is far harder to obtain, as it commonly requires fieldwork and manual data collection, which is costly, time-consuming, and would likely only be for a very small portion of polygons that are included in the study regions. There is also difficulty in finding data that reflects coral damage immediately after a TC event occurs across an entire reef system and whether the damage observed can be attributed to that TC or a number of extraneous variables if data were not collected prior to the event as well.

4. Conclusions

This Australia-wide assessment of TC risk to coral reef systems, as well as focus areas of the NR and the GBR, has shown that the risk of TC impact on corals can vary from very low to high depending on the cumulative hazard, exposure, and vulnerability. Wind hazard is very high for both reefs around 22–23°S. However, key findings exhibit that coral exposure ranges from very low to medium with a small amount of high exposure, and coral vulnerability is very high across the NR and a large portion of the GBR. The cumulative coral risk of polygons displayed a large amount at high and very high risk primarily in the northern NR corals and towards the southern end of the GBR. This work's identification of hazard, exposure, vulnerability, and overall risk for each individual polygon could help in the management and conservation of marine systems by focusing on the health of corals, as a keystone species, and making decisions to improve recovery efficiency and the building of resilience to oncoming disturbances. It can also inform decision making in reducing the impact humans directly have in disturbing corals via recreation, fishing, and watershed and marine-based pollution. This study also provides another example of how such a TC risk assessment methodology can be used to build understanding of regions at risk and help inform risk reduction efforts.

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