Temporal global trends of human population and dependency on coral reefs

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A thesis submitted for the degree of Doctor of Philosophy in
Biological Sciences

School of Life Sciences
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August 2022

Abstract

Research on human populations and dependency on coral reefs is relatively sparse, and often uses recycled statistics that have not been updated for many years. In light of climate change on coral reefs, its vital that continual assessments not only on coral reef ecosystems, but additionally the communities that rely on them is maintained in order to inform climate resilience. I aimed to 1) update statistics and create a long-term dataset of human populations near coral reefs, and 2) develop a human dependency framework that is reproducible and adaptable to newly available data. Using openly accessible data, of LandScan and global coral reef distribution map, I found that nearly 1 billon people live within 100 km of coral reefs in 2020. I developed a conceptual human dependency framework, which encompassed four pre-defined dependency categories, of fisheries, tourism, coastal protection and nutrition. Using an indicator approach, openly accessible data was collected for each category. The Human dependency on coral reef index (HDCRI) was developed and calculated, and were complemented by hybrid learning techniques. Human dependency "profiles" were created, and presented, how countries were dependent on coral reef ecosystems and what indicators were driving the dependency. The conceptual framework, aimed to shift thinking of human dependency on a linear scale from low to high dependency, towards a more holistic view on human dependency. The human dependency framework and population methods, were designed to be reproducible and adaptable to different scales of data (e.g. regional and national levels), and updated with improved datasets. The outputs of these studies are aimed to improve coral science by facilitating human aspects to research, additionally, to create more informed decision making to policymakers in distributing funds and resources. Finally, to

facilitate a novel tool of insurance as a form of climate resilience, for coral reefs and the humans that depend on them.

Acknowledgements

I would like to thank the University of Essex for funding the PhD through the Faculty Research Studentship. I sincerely thank my supervisors Dr Michelle Taylor and Dr Spyridon Vrontos for their support throughout the PhD journey, even when times were tough I felt supported and guided through these times. To my friends and family, for their support throughout my life and cheering me on to pursue my passion for research and science.

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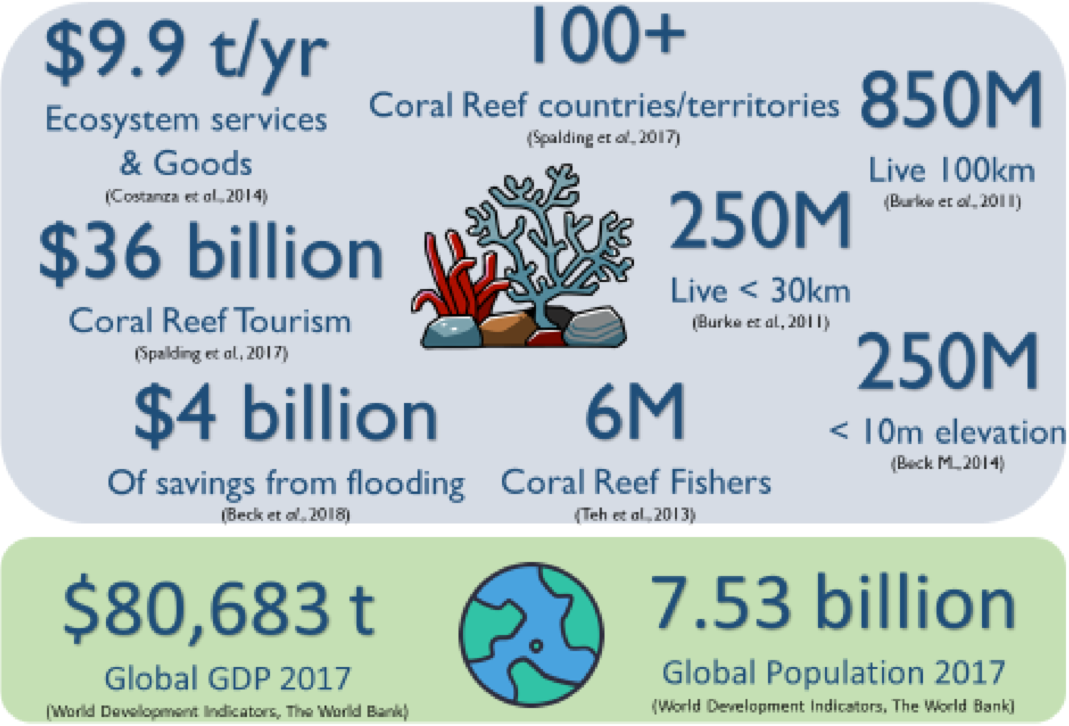


Coral reefs are one of the most diverse, complex and productive ecosystems on the planet providing human populations with livelihoods and welfare that reaches far beyond the shores of the reefs themselves. These ecosystems are under threat by global anthropogenic climate change and, the impacts of environmental change and loss of ecosystem function are currently being studied and documented. Coral reefs provide ecosystem services for up to 1 billion people and generate up to $9.9 trillion/yr-1 with ecosystem services and goods, $36 billion/yr^{-1} in coral reef tourism, and provide more than $4 billion/yr^{-1} worth of flood savings. Studies implicate that many of these services and goods, and dependent human populations, will be affected detrimentally by climate change. Climate change threats such as increased sea surface

temperature, ocean acidification and sea-level rise will bring about cascading effects ecologically and socially on and around coral reefs. Human livelihoods and welfare, particularly food security and income from coral reef fisheries are the most recognised areas in which humans will be impacted. Novel solutions are required to ensure that ecosystems and society can become climate resilient. Insuring coral reefs against impacts and protecting the livelihoods of those relying on them, is a potential tool as a part of wider schemes to provide climate resilience. However, data available on the number of people at risk from climate-change on coral reefs required a major update – a study presented within. Additionally, human dependency on coral reefs requires refinement and a more streamlined methodology to create standardisation in this field of research. Outputs will be put forward to coral scientists, managers, policymakers and insurance companies to create applied solutions to climate resilience, additionally, to make informed decisions about distribution of limited funds and resources.

Introduction

Coral reefs have been identified as one of the most sensitive and fragile ecosystems in the face of ongoing global climate change (Hoegh-Guldberg et al., 2018; Pandolfi, 2015; Walpole & Hadwen, 2022). We are witnessing and experiencing the impacts of climate change at global (Logan et al., 2021) and regional scales (Walther et al., 2002). Consequently, extreme climatic events such as severe storms, heat waves, and tornados are on the increase in frequency and magnitude (Zabin et al., 2022) with coral reefs ecosystems on the frontline of global change. Studies have already provided evidence of current climate change impacts on coral reefs. Fisheries, coral, and fish communities are impacted by increased sea surface temperature and ocean acidification to detrimental effects (Hughes, Kerry, et al., 2017; Pendleton et al., 2016a; Sunday et al., 2017). In addition, sea-level rise has the potential to cause major flooding (Beck et al., 2018; Kulp & Strauss, 2019), if coral reefs are not able to "keep up" in terms of vertical growth (Hibbert et al., 2016) as mean water depth will increase, inhibiting the ability for the reef structure to modulate wave energy regimes (Perry et al., 2018).

Healthy coral reefs deliver many ecosystem services that are fundamental to human health, wellbeing and livelihoods (Aswani et al., 2018; Harborne et al., 2017; Hernández-Blanco et al., 2022; Sweet et al., 2021; Woodhead et al., 2019), such as providing a source of protein and nutrients to many of the poorest communities in the world (Donner & Potere, 2007). Many socio-ecological studies of coral reefs have highlighted the importance of linking the natural world and human societies during the assessments of climate change impacts (Hicks et al., 2016; Cinner et al., 2016a; Sweet et al., 2021). Worryingly, coral reefs capacity to provide ecosystem services has declined by half since the 1950s (Eddy et al., 2021).

Studies have aimed to assess the global communities that may be affected by coral reef decline through local and global disturbances (Hinrichsen, 2011; C. Wilkinson, 2004a). Seminal papers and reports such as Wilkinson (2004) and Reefs at Risk Revisited (Burke et al., 2011a) are cited in over 1897 papers combined to date (correct at time of writing July 2022). The statistics are often cited for the number of people that depend / live near coral reef ecosystems or are vulnerable to local and global disturbances on coral reefs. The population data from these studies date back to the 1990s and 2007 respectively. With open access to more up-to-date global population databases now there is a clear need to update these widely used statistics. This is precisely the research I undertook in preparing Chapter 2: An assessment of people living by coral reefs over space and time (Sing Wong et al. 2022).

In addition to up-to-date population data, I provide improved maps of humans populations living by coral reefs. These are important outputs given the immediacy of this pressing issue; highlighted in many international publications but also with the release of the *IPCC Special Report: Global Warming of 1.5 ºC*, recent COP 26 held in Glasgow in 2021, and with extreme climatic events of heat waves and subsequently marine heat waves occurring right now globally. Global warming and climate change are increasingly being recognised as a unrelenting global issue that must be dealt with rapidly. In order for these issues to be addressed properly and appropriately, up to date statistics, that are the best current representative of known data and are essential for decision-making.

In an attempt to protect the livelihoods and welfare of a coral reef-dependent community an insurance policy was proposed to local Mexican Government in Quintana Roo. Led by The Nature Conservancy and insurance company Swiss Re; the local government and tourism sector recognised the importance of protecting the reef and launched the “Coastal Zone Management Trust”. Not only will this fund pay for beach and reef maintenance, but it will also allow the local community to take out an insurance policy to protect the beach and reef. The policy is triggered when wind speeds exceed 100 knots and does not cover coral bleaching or algae overgrowth (The Nature Conservancy, 2017). This is a novel and potentially valuable way to protect local interests against some of the problems climate change will bring. It also puts direct financial values on coral reefs and their goods and services – this is perhaps a double-edged sword but does focus research on this important task – valuing coral reefs.

The aim of this literature review is to investigate the studies, concepts and methodology of (1) how humans depend on coral reef ecosystems for their livelihoods and welfare,

(2) how climate change impacts coral reef ecosystems, (3) how humans are impacted by climate change to coral reef ecosystems (4) how coral reefs are valued, and (5) climate change insurance as a novel solution for climate resilience. A thorough review of these topics will facilitate the development of an informed and holistic approach to developing novel ways of protecting and mitigating climate change impacts to coral reefs and dependent societies. First, we must understand some of the basic information and statistics of the current status of coral reefs in general.

The Importance of Coral Reefs

Warm-water coral reefs are found in shallow tropical waters, ranging from 30°N and 30°S (Hoegh-Guldberg, Poloczanska, et al., 2017) (Figure 1) and are highly restricted in their geographic distribution. Coral reefs require areas of sunlit, warm, shallow and alkaline waters (Hoegh-Guldberg, Poloczanska, et al., 2017) in order for corals to produce the large quantities of calcium carbonate required to form solid reef structures (Beck & Lange, 2016; Watanabe & Nakamura, 2018). Coral reefs cover less than 0.1% of the world's oceans (Beck & Lange, 2016), are extremely biodiverse, hosting up to one quarter of all marine fish species (Laffoley & Baxter, 2016) and are among the most productive and complex ecosystems found in the world (Bellwood & Hughes, 2001; Harborne et al., 2017; Mumby & Steneck, 2008).

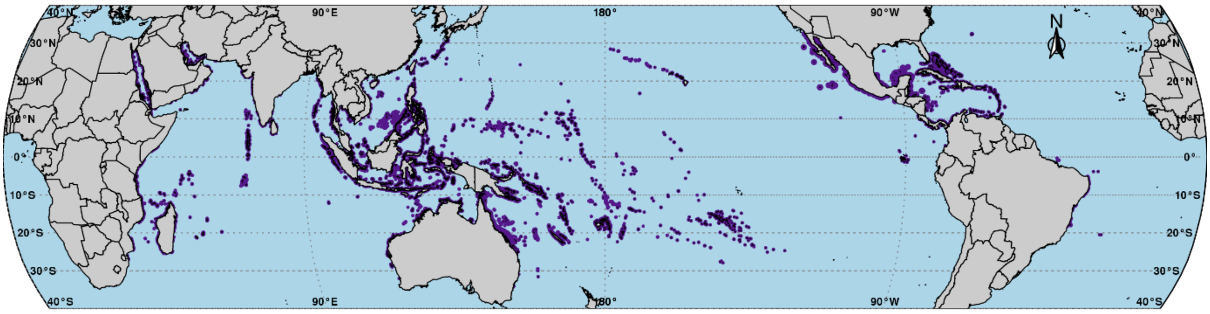


Figure 1. The global range of coral reef ecosystems (purple) (UNEP-WCMC et al., 2018).

Coral reefs are of significant importance as they support millions of livelihoods and human welfare (Burke et al., 2011a; T. S. H. Martin et al., 2017; Ruppert et al., 2018). They do this by providing ecosystem services and goods (Table 1). The definitions of ecosystem services have evolved over the 20+ years in the field (Costanza et al., 2017; Woodhead et al., 2019). Ecosystem services defined by Costanza et al. (2017), "*are the ecological characteristics, functions, or processes that directly or indirectly contribute to human wellbeing: that is, the benefits that people derive from functioning ecosystems*". Coral reefs encompass many ecosystem services, and have a total value of $9.9 trillion/year (Costanza et al., 2014); the global GDP in 2021 was valued at $96.1 trillion (World Development Indicators, The World Bank), therefore around 10% of the global GDP.

Table 1. Comparison of four of the main ecosystem services classification systems used worldwide and their differences and similarities. Taken from Costanza et al. (2017).

	Costanza et al., 1997	**Millennium Ecosystem Assessment, 2005**	**The Economics of Ecosystems and Biodiversity (TEEB), 2010**	**The Common International Classification of Ecosystem Services (CICES), v.4.3**
Provisioning	Food production *(13)*	Food	Food	Biomass - Nutrition
	Water supply *(5)*	Fresh water	Water	Water
	Raw materials *(14)*	Fibre, etc.	Raw materials	Biomass - Fibre, energy & other materials
		Ornamental resources	Ornamental resources	
	Genetic resources *(15)*	Genetic resources	Genetic resources	
		Biochemicals and natural medicines	Medicinal resources	
	X	X	X	Biomass - Mechanical energy
Regulating & Habitat	Gas regulation *(1)*	Air quality regulation	Air purification	Mediation of gas- & air-flows
	Climate regulation *(2)*	Climate regulation	Climate regulation	Atmospheric composition & climate regulation
	Disturbance regulation (storm protection & flood control) *(3)*	Natural hazard regulation	Disturbance prevention or moderation	Mediation of air & liquid flows
	Water regulation (e.g. natural irrigation & drought prevention) *(4)*	Water regulation	Regulation of water flows	Mediation of liquid flows
	Waste treatment *(9)*	Water purification and waste treatment	Waste treatment (esp. water purification)	Mediation of waste, toxics, and other nuisances
	Erosion control & sediment retention *(8)*	Erosion regulation	Erosion prevention	Mediation of mass-flows
	Soil formation *(7)*	Soil formation *[supporting service]*	Maintaining soil fertility	Maintenance of soil formation and composition
	Pollination *(10)*	Pollination	Pollination	Life cycle maintenance (incl. pollination)

	Costanza et al., 1997	**Millennium Ecosystem Assessment, 2005**	**The Economics of Ecosystems and Biodiversity (TEEB), 2010**	**The Common International Classification of Ecosystem Services (CICES), v.4.3**
	Biological control *(11)*	Regulation of pests & human diseases	Biological control	Maintenance of pest- and disease-control
Supporting & Habitat	Nutrient cycling *(8)*	Nutrient cycling & photosynthesis, primary production	X	X
	Refugia (nursery, migration habitat) *(12)*	'Biodiversity'	Lifecycle maintenance (esp. nursery) Gene pool protection	Life cycle maintenance, habitat, and gene pool protection
Cultural	Recreation (incl. eco-tourism & outdoor activities) *(16)*	Recreation & eco-tourism	Recreation & eco-tourism	Physical and experiential interactions
	Cultural (incl. aesthetic, artistic, spiritual, education, & science) *(17)*	Aesthetic values	Aesthetic information	
		Cultural diversity	Inspiration for culture, art, & design	
		Spiritual & religious values	Spiritual experience	Spiritual and/or emblematic interactions
		Knowledge systems Educational values	Information for cognitive development	Intellectual and representative interactions

a) Costanza et al. (1997) did not make a division into main categories; numbers (1–17) refer to Table 1
b) CICES is still in development. The list included here is v. 4.3 downloaded on 7 May 2017 from https://cices.eu/cices-structure/.

Despite their importance and value, most coral reefs are facing threats on both local and global scales. The type of disturbances a reef is faced with varies with location (Ruppert et al., 2018; Wilson et al., 2006; Wolff et al., 2015). In the U.S. and Australia, the aesthetic value of the reef is of high importance but through high levels of tourism the reefs are damaged through the diving industry, and degraded through on land tourist infrastructure developments (Hanich et al., 2018). Reefs located in more developing countries are most often exploited for fisheries or otherwise impacted through coastal development (Ruppert et al., 2018; Smith et al., 2016). Though local disturbances coupled with increasing atmospheric carbon dioxide critically impacts ecosystems, climate change overall poses the greatest threat to coral reefs globally (Heron et al., 2017).

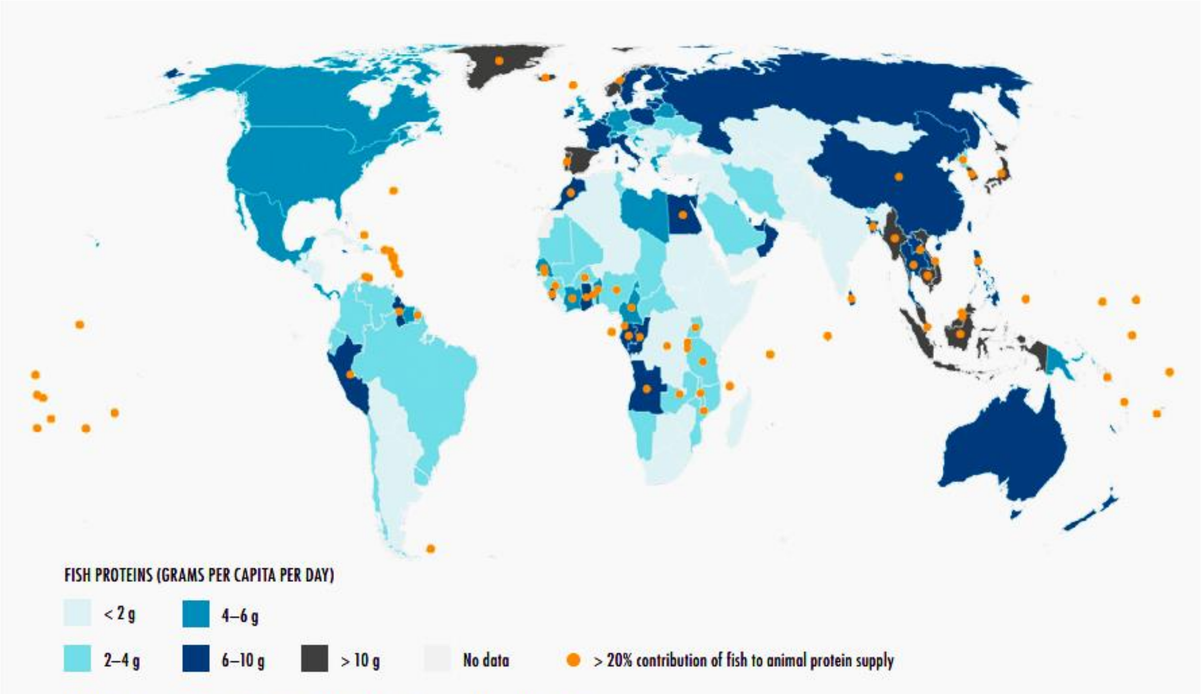
The global distribution of coral reefs and the countries they are found in are governed under numerous forms of legislation and are often difficult to manage. Studies that have attempted to encompass the global range of coral reefs have varied in the number of countries that are included in their studies (Table 6). This variation is usually due to the experimental design, and/or data availability, which can reduce or eliminate particular countries from the study. A comprehensive list of coral reef countries is difficult to come across, with the most extensive lists having being adapted from Spalding et al. (2001) and extracted from GIS maps (Burke et al., 2011a). Countries named in these studies are sometimes grouped into territories, for example, the United Kingdom includes territories of the British Indian Ocean Territory, Anguilla, Bermuda, Cayman Islands, Pitcairn, Turks and Caicos Islands, British Virgin Islands (Spalding et al., 2001). This is a crucial point to realise when aiming to carry out global studies as this could misrepresent or misguide management and policy that impact the reefs and society at local scales.

A common management method to protect and conserve coral reef ecosystems is to designate marine protected areas (MPAs). Within MPAs across the globe, many different management strategies are adopted, dependent on the local and/or national goals. The MPAs may even take different forms from Locally Managed Marine Areas (LMMAs), Marine Reserves and National Parks (Burke et al., 2011a), to name a few, however, they are fundamentally aiming for similar goals. The IUCN definition of a protected area is ‘a clearly defined geographical space, recognised, dedicated and managed, through legal or other effective means, to achieve the long-term conservation of nature with associated ecosystem services and cultural values' (Thomas et al., 2014). Of the global coral reef area which covers 280,000 km^2 (Costanza et al., 2014), coral reef MPAs cover approximately 150,000 km of shorelines (Burke et al., 2011a), approximately 53% to date. However, many of these protected areas can be questionable in terms of the effectiveness of the management and regulation; sometimes these are described as 'paper parks', where ecological and social goals are simply legislated on paper (Gill et al., 2017) and not put into action.

Human livelihoods, welfare and coral reefs

Human livelihoods and welfare are supported by coral reefs through providing a critical source of economic and food security benefits (J. Cinner, 2014; Cottrell et al., 2019; Spalding et al., 2001), in addition to cultural practices (J. E. Cinner et al., 2013; Darling & D'agata, 2017), that benefit people worldwide directly and indirectly. Hernández-Blanco et al. (2022) state that "*Healthy ecosystems provide human well-being via ecosystem services, which are produced in interaction with human, social and built capital*".

The 2020 FAO report *"State of Fisheries and Aquaculture in the world"* stated that on average fish provided about 35 calories per capita per day in 2017, but this can exceed 100 calories per capita per day in areas that lack alternative food proteins. 3.3 billion people utilise fish for more than 20% of their average animal protein intake (FAO, 2020). Fish contributed 50% or more of total animal protein intake in Bangladesh, Cambodia, the Gambia, Ghana, Indonesia, Sierra Leone, Sri Lanka and some Small Island Developing States (SIDS) (Figure 2). In Indonesia coral reef fishers were estimated to be a community of 1.7 million, the highest out of coral reef fishery countries, followed by India with 959,000 and Philippines with 912,000; By contrast, Jordon was estimated to have only 90 coral reef fishers (L. S. L. Teh et al., 2013).



NOTE: Final boundary between the Sudan and South Sudan has not yet been determined.
SOURCE: FAO.

Figure 2. The contribution of fish to animal protein supply, average 2015 – 2017 (FAO, 2020).

Coral reef fisheries are the most prominent example of human livelihoods and welfare provided by coral reefs. Coral reef fisheries have been found to provide jobs to 6 million people, most of which are found in developing countries and over half in Southeast Asia alone (L. S. L. Teh et al., 2013). Fisheries are important for the health and welfare of coastal communities and are a primary source of food security, nutrition, and cultural identity (FAO, 2018; Sainsbury et al., 2018; Wamukota & McClanahan, 2017). Fish are crucial sources of bioavailable forms of micronutrients (the human body only requires tiny amount of them – iron, zinc, omega-3 fatty acids and vitamins) and are critical to children and pregnant women for child brain development (Golden et al., 2016); this is additionally important in lower-income countries where nutritional deficiencies are more severe and widespread (FAO, 2018). Teh and Pauly (2018) found that small-scale marine fisheries total catch was on average underestimated around two times in four Southeast Asian countries.

A study by Cinner (2014) discusses the growing appreciation of the non-material benefits coral reefs fisheries provide. This includes contributing to people's identity, lifestyle, and social norms of fishermen and the community. These non-material benefits can become more deeply rooted than material benefits such as income, which may not induce behavioural changes when given the option (i.e. changing jobs from fisheries). This study highlights the complexity of socio-ecological interactions and that providing an alternative livelihood may not be a mechanism to ease reef fishery pressure if it is not presented under the correct circumstances. Ingram et al. (2018) demonstrated that in Hawai'i cultural services (identified generally as non-material, intangible benefits and included cultural identity and connection to place which has been recognised at direct contributor to human well-being) were perceived to be the most impacted service to pressures (local and global).

Coral reef-related tourism is another example of livelihood and welfare benefits that are provided by coral reefs. Coral reef tourism is the most significant example of nature-based tourism from a single ecosystem and attracts foreign and domestic visitors which generates revenues in over 100 countries and territories (Spalding et al., 2017). The seminal paper by Spalding et al. (2017) mapped and valued globally coral reef tourism pre-covid. They divided tourism into "on-reef" where the activities such as diving, snorkelling, glass-bottom boating and wildlife watching would take place directly on reefs and was valued at $19 billion a year. The other form was classed "reef-adjacent" tourism and included everything from local seafood to enjoying the views, paddle-boarding, and other activities provided by the effect of sheltering from the adjacent reefs and was valued at $16 billion a year. These two forms of coral reef tourism totalled $36 billion a year. Spalding et al. (2017) also identified that 70+ countries and territories have million-dollar reefs – these reefs could generate more than $1 million per km^2; these could be found in the Florida Keys, Bahamas, Mexico, Indonesia, Australia, and Mauritius, to name a few. These examples demonstrate how ecotourism and nature-based tourism are critical for revenue and as a major source of employment (Hanich et al., 2018). Spalding et al. (2021) reviewed the implications of Covid-19 for nature and tourism. They found positives and negatives as a result of tourism collapse; with benefits to the natural environment (e.g. depressed coastal-fish stocks making provisional steps towards recovery) and conversely rises in illegal fishing, poaching and deforestation. As most tourism has a link or dependency on nature and natural ecosystems, they concluded that there is a greater need for the valuation of “nature-dependent tourism”.

Here we have highlighted the main pathways in which coral reefs provide livelihood and welfare to people. These demonstrate the value, benefits, and the social reach that can be obtained from coral reefs. However, additional human livelihoods and welfare include and are not limited to, medicinal research and resources (Beck & Lange, 2016; FAO, 2018), coastal protection (Beck et al., 2018), pollutant control (Barbier, 2017), traditional, cultural or religious significance (Barbier, 2017; J. Cinner, 2014), and carbon storage/sequestration (Barbier, 2017; de Groot et al., 2012a). Complex interactions between livelihood and welfare, and ecosystem pathways coupled with diverse societies, leads us to question the level of dependency coral reef communities have on the ecosystem.

Human dependency on coral reefs

We can assume that all the communities that live near coral reefs are dependent on them in some shape or form. While this is true, dependency on the reef can be very complex and difficult to disentangle on local, regional and/or global scales. It is widely known among the scientific community that high poverty communities are most dependent on ecosystem services and are most vulnerable to the degradation of these services (Yang et al., 2013).

Within coral reef studies, the proxies of dependency can vary from study to study and can often have ambiguous and/or confusing descriptions of how people are dependent on coral reefs. Table 2, provides a summary of how human dependency on coral reefs is depicted in literature; as it can often be difficult to demonstrate dependency; these values are frequently recycled in the introduction of many coral reef studies. Additionally, if a value is not directly given, a blanket statement of “millions of people are dependent on coral reefs” is regularly utilised.

Table 2. Summary of "human dependency" depicted across coral reef studies.

Project/ Paper	**Published data**	**Global Human Population**	**Population Description**	**Population Data**	**Source**
Reefs at Risk	1998	500 million people	Live within 100km of reefs	Date:NA, Gridded World Population Data (GWP)	(Bryant et al., 1998)
Reefs at Risk Revisited	2011	850 million people	Live within 100km of reefs	LandScan (2007)	(Burke et al., 2011a)
		250 million people	(within 30 km of reefs and less than 10 km from the coast)		
Wilkinson	2004	500 million people	depend on coral reefs for food, coastal protection, cultural items, and tourism income; probably 30 million	1990s	(C. Wilkinson, 2004a)
		30 million	of the poorest people depend entirely on coral reefs for food		
Coasts at Risk	2014	250 million people	live in low-lying exposed areas on the coast (< 10m elevation) and within 10 km of a reef or mangrove habitat	FOA 2012	(Beck, 2014)
		660 -820 million people	depend on fish for livelihoods		
		3 billion people	fish as important source of protein		
Foale *et al*	2013	120 million people	who benefit from marine ecosystem goods and services for fishery production, shoreline protection, and tourism	NA	(Foale et al., 2013)
Cruz-Trinidad *et al*	2014	130 million people	dependent on fisheries ecosystems for food, income, and livelihoods	CIA 2013	(Cruz-Trinidad et al., 2014)
Teh *et al*	2013	Millions of people	heavily dependent on the goods and services provided by coral reefs	(SEDAC) Global Rural-Urban Mapping Project 2010	(L. S. L. Teh et al., 2013)

Nevertheless, the descriptions of population (Table 2) within literature are logical and the rationale behind utilising the values and descriptions are reasonable. Still we must take care when recycling these values, especially global population data. The global population increased from 5 billion people to 7.5 billion people between 1990 and 2017 (United Nations, 2018). The UN predicted that the global human population will reach 8.6 billion in 2030, 9.8 billion in 2050 and 11.2 billion in 2100 (United Nations, 2017). A study by Wilkinson et al. (1994), stated that the world's population would increase to at least 8.5 billion by 2050. This variation in population estimates demonstrates the need for continuous updating of statistics used in research. And, contrary to some earlier predictions, human population growth has been gradually decreasing since the 1990's (Figure 3).

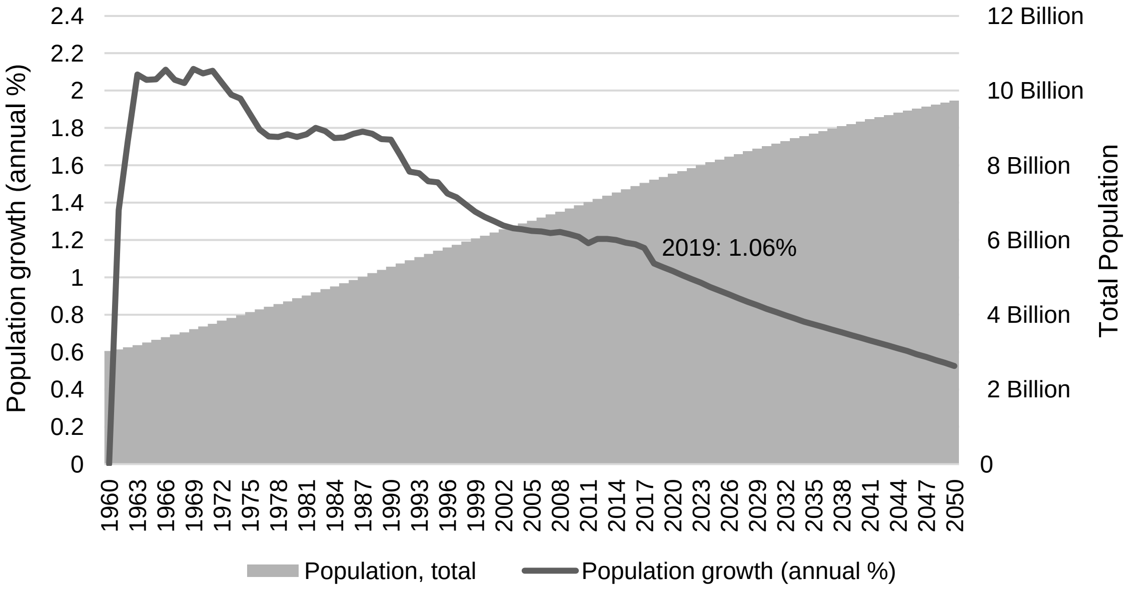


Figure 3. World population growth (annual %) and total population (billion) from 1960 to 2019 and projections up until 2050. Data taken from The World Bank (2018).

A loss of even 1 metre of coral reefs could cause billions of dollars' worth of damage to buildings and infrastructure due to storms and flooding (Beck et al., 2018). This means that by living near coral reefs human communities will certainly be dependent on that reef for coastal protection, even if there are infrastructures, such as sea defences available. This is one of the reasons why distance from reefs' has been used as one of the main dependency indicators/proxies in studies of human dependency on coral reefs; the most cited value being that taken from the Reefs at Risk Revisited report (Burke et al., 2011a). Cinner et al. (2022) linked key human-environment theories to inform the sustainability of coral reefs through four key metrics (top predator presence, reef fish biomass, trait diversity, and parrotfish scraping potential). They found that proximity to the nearest market best explained variation and was the strongest relationship to the four key metrics; this "agricultural location theory" is nascent in marine systems research and should be considered as a key theory in further marine research.

Pendleton et al. (2016) was able to map and identify areas of human dependence on coral reef ecosystem services, and those threatened by climate change. Dependency was scored (between 0 – 10) and mapped using two indicators at a country level: shoreline protection (number of people protected by coral reefs, obtained from Reefs at Risk Revisited) and coral reef fisheries (value of coral reef fisheries and number of coral reef fishers, obtained from; Teh et al., 2013). They investigated the threats of coral bleaching and ocean acidification as a result of climate change. Eight Degree Heating Weeks (DHW8) was used as a proxy for coral bleaching as this has been identified as the maximum threshold in which coral mortality s most likely to occur, with 6.1 DHWs identified as the mean optimum predictor for coral bleaching across the globe (Maynard et al., 2015; Van Hooidonk et al., 2016), with aragonite saturation

(Ω_{arag}) measurements were used for ocean acidification. Dependence on ecosystem services was the level of dependency on shoreline protection and coral reef fisheries combined. Coral bleaching was mapped using the date in the year DHW8 is first reached annually and Ω_{arag} levels mapped in 2050 all under IPCC RCP8.5 scenarios. This study is an exemplar study for understanding human dependency on coral reef ecosystems in the face of climate change, as it uses an uncomplicated indicator approach which can be replicated. Although the study is mapping the worst case scenario (RCP8.5), it still provides indications of where and when countries may be at risk of coral bleaching and ocean acidification effects. The methods applied in this study to calculate dependency used a normalised scoring systems and reported z-scores. Though z-scores can be a useful tool to indicate and compare dependency from two different data types, it relies heavily on the accuracy of the raw data and does not infer interdependency between variables.

A recent study by Selig et al. (2018) mapped the global human dependence on marine ecosystems. They produced conceptual models that were designed to be repeatable, scalable, and applicable across ecosystems and incorporate additional services and data. From expert opinion, they identified four key types of dependence on marine resources: nutritional, economic, coastal protection, and cultural (Table 3). Indicators of the four key dependency types were transformed to meet assumptions of normality and standardised [0-1], cultural indicators were not readily available on a global scale, therefore, were not modelled. They developed a quantitative framework based on three key mechanisms: the magnitude of benefit of the ecosystem service, the susceptibility of the human population to a loss of that benefit, and the level of substitutability of that benefit. The general form of the framework is:

$$Dependence = B \times \left(\frac{\bar{C} + (1 - \bar{S})}{2}\right)$$

where B is the magnitude of the ecosystem benefit of the service, $\overline{C}$ is the mean of the susceptibility indicators and $\overline{S}$ is the mean of substitutability indicators. The framework is based on current levels of benefit and does not take into account sustainability, therefore the dependency calculated for current states. The results of the study allowed them to quantify country dependence on the 3 key dependency types and overall dependency. They identified that more than 775 million people live in areas of relatively high dependency on marine ecosystems, with Indonesia ranking as the most dependent followed by the Philippines. This study demonstrated and applied the need for more quantitative methods for human dependency, in addition to indicating where dependency is higher across dependency types. This will allow for more informed management and decision-making.

Table 3. Description of datasets used in human dependency analysis (indicators were only included if the data was globally and spatially explicit). Taken from Selig et al. (2018).

Indicator	**Type of dependence**	**Mechanism**	**Year**	**Data source**	**Native dataset resolution**
Percentage of marine dietary protein to all animal protein	Nutrition	Magnitude of benefit	2011	(FAOSTAT 2012)	National
Percentage of underweight children under 5	Nutrition	Susceptibility	2005	(Center for International Earth Science Information Network - CIESIN - Columbia University 2005)	0.25 degrees
Dietary diversity I - marine protein to all dietary protein	Nutrition	Substitutability	2011	(FAOSTAT 2012)	National
Dietary diversity II - marine fat to all dietary fat	Nutrition	Substitutability	2011	(FAOSTAT 2012)	National
GDP	Nutrition, Economic, Coastal Protection	Substitutability	2005	(Nordhaus et al. 2011)	0.5 degrees
Percentage of GDP from fisheries revenues (exports + public fisheries access agreements)	Economic	Magnitude of benefit	2011	(Directorate-General for Maritime Affairs and Fisheries 2017; FAO 2014; World Bank 2014a; Yeeting et al. 2018)	National
Percentage of fisheries jobs to total jobs	Economic	Magnitude of benefit	2003	(Teh and Sumaila 2013; The World Factbook 2014)	National
GDP trend	Economic	Susceptibility	2010-2011	(World Bank 2014b)	National
Unemployment rate	Economic	Susceptibility	2011	(World Bank 2014c)	National

Education	Economic	Substitutability	2011	(United Nations Statistics Division 2014)	National
Governance	Economic, Coastal protection	Substitutability	2011	(Kauffman et al. 2014)	National
Exposure	Coastal protection	Magnitude of benefit	Various (see exposure indicators)	(Braaten et al. 2011; Jones et al. 2012; Knapp et al. 2010)	0.167 degrees (from derived datasets below)
Tropical storm frequency	Coastal protection	Magnitude of benefit (Exposure)	1900-2011	(Knapp et al. 2010)	Point data of storm tracks
Sea-level rise	Coastal protection	Magnitude of benefit (Exposure)	2011	(Braaten et al. 2011)	0.0083 degrees (1 km*)
Coral reef locations	Coastal protection	Magnitude of benefit (Exposure)	2011	(Burke et al. 2011)	0.0083 degrees (1 km*)
Mangrove locations	Coastal protection	Magnitude of benefit (Exposure)	2011 (data from 2000s)	(Giri et al. 2011)	0.00027 degrees (30 meters*)
Population density in the Low elevation coastal zone (LECZ)	Coastal protection	Susceptibility	2007	Jones et al, in prep	0.0083 degrees (1 km*)
Density of impervious surfaces	Coastal protection	Substitutability	2001	(Elvidge et al. 2007)	0.0083 degrees (1 km*)

The level of dependency on marine ecosystems varies across the globe. Access to alternative livelihoods is often a strong indication of dependency to coral reefs, and the ability to adapt to environmental change and reduce pressures on local ecosystems. Projects and interventions have been initiated around the world to ease community dependency on reef resources (Obura et al., 2008) and reduce environmentally damaging activities (Wright et al., 2016) with the aim of creating more sustainable livelihoods and increasing potential conservation benefits (Porter et al., 2018).

Within coral reef communities, particularly in less-developed countries, dependency is viewed as very high on subsistence fishing (Porter et al., 2018). An example of an alternative livelihood to fishing is seaweed farming; which has been introduced to remote coastal communities in Indonesia and the Philippines (J. Cinner, 2014). The FAO (2018) reported that Indonesia seaweed farming production has grown exponentially from 4 million tonnes in 2010 to over 11 million tonnes in 2015 and 2016. However, a study by Cinner (2014) demonstrated that providing alternative livelihoods may not always have the desired effect it was originally intended for. The seaweed farming intended to reduce fishing pressure however it was taken up mainly by females and children, resulting in household incomes becoming supplemented with no reduction in fishing pressure as desired. Additionally, marine social-ecological systems are highly variable and coupled with open-access regimes can incentivise more destructive fishing methods to achieve greater catch per unit effort. This can result in the system becoming trapped in an increasingly degraded and vulnerable state (Ferrol-Schulte et al., 2013). Thus, having alternative livelihoods to fishing does not always set out what it intende to achieve.

Defining human dependency on coral reef ecosystems is a complex interaction between ecological (e.g. fisheries productivity/fish biomass), economic (e.g. GDP, %

of GDP marine products export, and % GDP of reef tourism), and social factors (e.g. total population, population density, % of protein from fish, and number of underweight children). These factors should be directly considered when prioritising research. This will facilitate in identifying where help is needed for people in the face of environmental change and coral reef decline (Pendleton et al., 2016a).

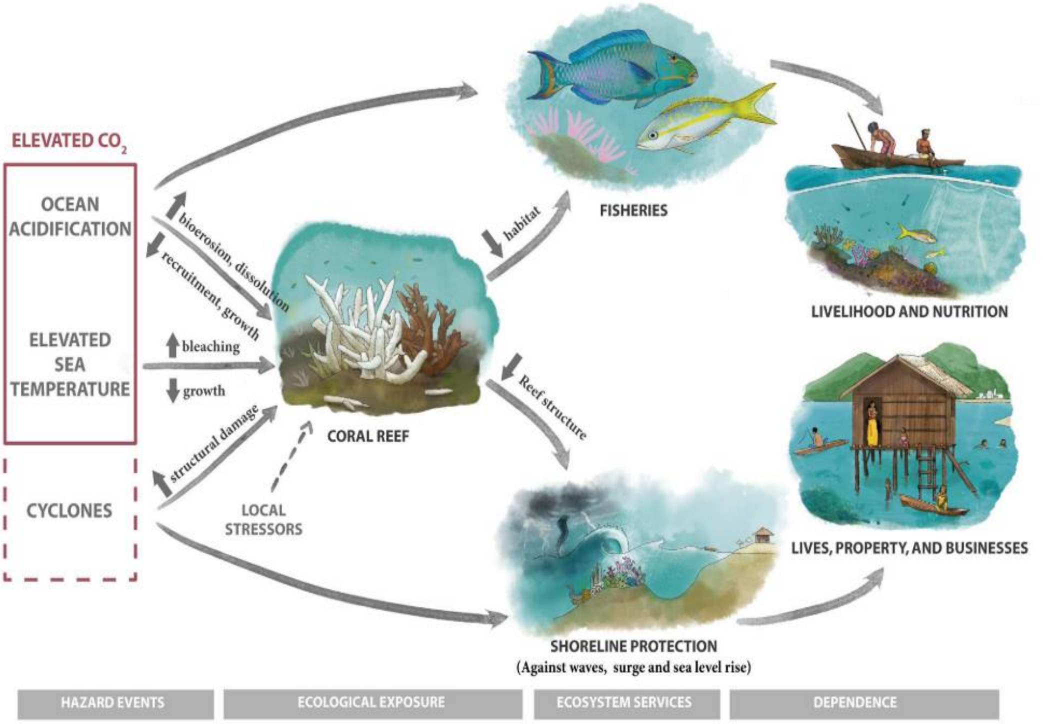


Figure 4. A conceptual diagram linking stresses related to increased atmospheric CO2 (elevated sea surface temperature and ocean acidification), storms, and local stressors to coral reef condition, selected ecosystem services provided by reefs, and human dependence on these ecosystem services. Solid lines represent relationships evaluated in this study. Taken from Pendleton et al. (2016).

Climate change and coral reefs

It has been stated that coral reefs are on the frontline of global climate change; this is due to coral reefs being fragile and delicate systems that require a fine balance of environmental conditions to thrive. The IPCC special report of “Global Warming of 1.5°C” (IPCC SR1.5) demonstrates that warm water coral reef systems are currently facing very high risks of impacts which could lead to irreversible change due to climate-related hazards (IPCC, 2018a). In this section, I will discuss the ecological impacts of climate change on coral reefs.

Much research has been done on climate change and coral reefs. The most recognised research areas are investigating (1) increased sea surface temperature as a cause for mass coral bleaching and coral reef loss (Ban et al., 2014; Cinner et al., 2016b; Van Hooidonk et al., 2016; Heron et al., 2017; Hughes et al., 2017), regime shifts (Hughes, Barnes, et al., 2017; Hughes et al., 2010; Norström et al., 2016), and coral reef fish physiology (Messmer et al., 2017), (2) increased atmospheric CO_2 causing ocean acidification and resulting in lower coral reef accretion (Albright et al., 2016) and changes in population dynamics of marine organisms – physiology, behaviour and fitness (Albright et al., 2016; Kroeker et al., 2013). Less studied areas focus on increased sea level rise (Beck et al., 2018; Perry et al., 2018) and loss of coral reefs for coastal protection (Beck et al., 2018).

A study by Hoegh-Guldberg et al. (2017), stated that coral reef ecosystems are likely to disappear by 2040 - 2050 even in the lower greenhouse gas emissions scenario of RCP4.5. Adaptation of coral reefs to rapid ocean warming and ocean acidification is minimal, and given that coral reefs are long-lived would suggest slow rates of evolution (Hoegh-Guldberg, Poloczanska, et al., 2017). Norström et al. (2016) presented safe operating levels of CO_2, to avoid chronic mass bleaching and ocean acidification, to be 340 to 480 ppm and 480 to 750 ppm respectively. These safe operating spaces were derived from multiple studies and provided to ensure that coral reefs ecosystems and the services they provide to human societies endure the change through the Anthropocene. On the other hand, a more conservative value for the healthy operating space for coral reefs were defined to be around 320 - 350 ppm (Laffoley & Baxter, 2016). A summary of healthy operating spaces and major thresholds to environmental change can be found in Table 4; these values have been derived from empirical studies, literature reviews, and climate model projections.

Pre-industrial levels of atmospheric CO_2 was on average about 280 ppm (Ciais et al., 2013). The current level of atmospheric CO_2 is ~411ppm as of February 2019 (Mcgee, 2017); we are exceeding values that are within the safe operating spaces for coral reef ecosystems. The major players in coral reef and climate change studies are typically (1) increased sea surface temperature and (2) ocean acidification, however, I will also delve into studies on (3) sea level rise and (4) deoxygenation effects on coral reef ecosystems below.

Table 4. Summary of healthy operating spaces and major thresholds to environmental change of coral reef communities.

Thresholds for major changes to coral communities

Source	**Thermal Stress**		**carbonate-ion concentrations ([carbonate]**	**approximate aragonite saturation ~ Ω aragonite**		**[CO2]atm**	
Hoegh-Guldberg *et al.* (2017)	*(+2°C)*		*200 µmol kg−1*	*3.3*		*480 ppm*	
Laffoley and Baxter, (2016)	>4°C DHW 1°C DHM	Coral Bleaching				320 - 350 ppm	Healthy coral reefs
	>8°C DHW 2°C DHM	Coral Mortality					
Guinotte *et al*. (2003)				> 4.0	Optimal coral accretion		
				3.5-4.0	Adequate coral accretion		
				3.0-3.5	Low coral accretion		
				<3.0	Extremely marginal coral accretion		
Norström *et al.* (2016)	(+) 1 - 2 for 3 - 4 weeks	Coral Bleaching & Mortality				340 to 480 ppm	Chronic mass bleaching safe operating spaces
						480 to 750 ppm	Ocean acidification safe operating spaces
						560 ppm	Corals reefs will cease to grow and start to dissolve

Increased sea surface temperature

The most recognised climate change driver in the oceans is increased sea surface temperature (SST). Coral reef communities are well known for thriving in conditions close to their temperature upper limits (Laffoley & Baxter, 2016; Lough et al., 2018); this makes them vulnerable to 'small' changes in temperature (Gattuso et al., 2015). Coral bleaching can occur when temperature exceeds the summer maxima by 1°C (Donner et al., 2005). Studies are predicting annual coral bleaching events in the coming decades (Hughes et al., 2018), with increasing cases of reefs experiencing multiple bouts of bleaching in relatively short time frames (Hughes et al., 2017) and increased frequency in mass bleaching events (Lough et al., 2018). This would be devastating to coral reef ecosystems and very likely cause coral reef decline if bleaching reaches mortality levels. Typically coral communities take at least 15 to 25 years to recover from mass mortality events (Heron et al., 2017). However fast growers and quick colonising species can have recovery time between 10 to 15 years (Hughes, Kerry, et al., 2017). Clearly with bleaching occurring across much shorter time frames currently reefs do not have sufficient time to recover.

Increased SST, is also linked to increased frequency of coral disease outbreaks, changing environmental conditions can lead to increased viral production in corals, leading to further degradation (Thurber et al., 2017). A study by Maynard et al. (2015), demonstrated that coral diseases are as likely to cause coral mortality as bleaching in the coming decades. Increased SST has experimentally been found to reduce the size of coral reef fish (Messmer et al., 2017). Climate-induced reduction is fish body size will have critical ramifications for fisheries production and knock-on effects for trophodynamics and ecosystem functioning. Additionally, major species distribution shifts could cause huge impacts on ecosystem functioning and health with fish species favouring deeper water due to ocean warming (Pecl et al., 2017).

With climate change causing coral mortality and consequently the loss of coral cover (Bruno & Valdivia, 2016), regime shifts to alternative states (macro-algae, bivalves, sponges, tunicates and zoanthids; Hughes et al., 2010) could occur due to the loss of their natural coral competitors in short-term events (Hughes et al., 2013). Additionally, changes in trophodynamics can be attributed to overfishing and environmental shocks, with changes population dynamics of coral reef organisms (Cinner, et al., 2016).

Ocean Acidification

Ocean acidification (OA) is the reduction of pH in the ocean waters. The increased dissolution of carbon dioxide into the oceans has increased hydrogen ion concentration (therefore decreasing pH) and decreased the carbonate ion concentration (Hoegh-Guldberg, Poloczanska, et al., 2017). Aragonite saturation (Ω_{arag}) is the common metric used in ocean acidification studies and climate models for coral reefs.

There is clear evidence that carbonate accretion becomes zero or negative when Ω_{arag} falls below 3.3 (Hoegh-Guldberg, Poloczanska, et al., 2017). This means that calcifying organisms, such as reef-building corals, bivalves, and molluscs, are negatively impacted in terms of survival, calcification, growth, development, and abundance (Kroeker et al., 2013). The calcifying process is a critical mechanism in the maintenance of coral reef ecosystems for building and providing habitats, additionally, this provides a direct eco-service to human communities by replenishing beaches and providing coastal protection (Andersson & Gledhill, 2013).

The Net Ecosystem Calcification (NEC) is the total calcification minus total calcium carbonate ($CaCO_3$) dissolution (Andersson & Gledhill, 2013); if this is in a positive state we refer to this as accretion and the coral reef ecosystem is in a state of growth, a negative state is dissolution and the reef is eroding (Albright et al., 2016; Beck & Lange, 2016). Changes in ocean chemistry can be termed as a “silent killer”, ecosystem responses are not as visible compared to coral bleaching and therefore is extremely important to monitor.

A review by Andersson and Gledhill (2013) on ocean acidification and coral reefs, provides great insight to the complex mechanisms of ocean acidification, bio-erosion and the dissolution of coral reefs. Additionally, they report past and present Net Accretion and present a warning in using the NEC and Ω_{arag} relationships to predict future effects of OA because of the strong coupling effect of biogeochemical processes and their effect on the seawater chemistry. They state future issues should resolve whether decreasing NEC is a function of OA as a result of decrease in calcification, an increase in dissolution, or a combination of both.

Sea-Level Rise

Coral reefs have historically responded to sea-level rise (SLR) in three ways (1) “keep-up”, here reefs maintain crests at or close to sea level, (2) “catch-up” where reef growth occurs in deeper water as sea-level rise exceeds the rate of growth and reefs catch up when SLR decreases or ceases, this often produces a successive change in coral assemblages across the depth gradient, and (3) “give-up”, where there is a sudden stop in growth probably due to sudden rises in sea level or change in environmental or oceanographic conditions and growth can no longer keep up, essentially ‘drowning” the reef (Hibbert et al., 2016). These responses to historic sea-level rise are now what today's coral reefs face with average global sea levels increasing by 3.2 mm year^{-1} (over 1993–2010) (Hoegh-Guldberg, Poloczanska, et al., 2017). Future projections of climate change under the RCP4.5 scenario, predicts that many reefs will not sustain accretion rates to track SLR, and under RCP8.5 scenarios most reefs will experience an average water depth increase of more than 0.5m by 2100 (Perry et al., 2018).

If coral reefs are not able to accrete at rates that keep up with SLR there are some major consequences for the ecosystem and the human communities that rely on them. Coral reefs provide critical coastal protection and have been found to absorb on average 97% of wave energy (Ferrario et al., 2014) reducing the risk for more than 200 million people who live in coastal exposed areas (Beck & Lange, 2016). A seminal study by Beck et al. (2018) valued the global flood protection savings provided by coral reefs. This study compared the flooding damage costs with and without reefs (1 metre loss of reef) and modelled this with sea level rise under the RCP8.5 in 2100 scenario. They found that with reefs under present day conditions can reduce storm damages by more than $4 billion. This value alone demonstrates the silent protective impact of coral reefs when intact.

Increased sea-level rise, coupled with increased SST and ocean acidification will cause losses of reef systems. Coastal protection from these reef systems are then lost and could cause major coastal erosion of connecting ecosystems such as seagrasses, mangroves and beaches (Gillis et al., 2017). All of which are extremely ecologically and economically important for human populations (Townsend et al., 2018; Weeks, 2017).

Coral reefs face many drivers of decline across local and global scales; we must remember that even though coral reefs are under greatest threat from global climate change. The continuous and persistent degradation of the ecosystem through local disturbances should not be ignored.

Human impact of climate change and coral reefs

Coral reef ecosystems can also be described as social-ecological systems (SES) (Ferrol-Schulte et al., 2013; Reyers et al., 2018). This has been defined as "a bio-geophysical system with its associated social agents and institution in a problem context" (Ferrol-Schulte et al., 2013). The ecological impacts of climate change on coral reefs ecosystems have cascading effects on the human communities that rely on and utilise them (Rabinowitz & Conti, 2013). Changing marine ecosystems can cause sudden economic shocks and/or food crises (Niehörster & Murnane, 2018). For example, large toxic algae blooms could have major impacts on fisheries and human health implications; causing neurological illnesses through the consumption of fish containing ciguatera toxin produced by dinoflagellates (Grattan et al., 2016; Rabinowitz & Conti, 2013). In developing countries where dependency on coral reef fisheries are high for income and sustenance, this could have devastating effects on the communities, particularly if there are no mitigation or adaptation processes in place. Additional human health implications of coral reef decline is through biotechnology and pharmaceutical development; advancement of medical research could be limited or prohibited – losing medical potential before its even discovered. There is a wide variety of research showing the utility of many coral reef-related organisms - Research has found anticancer agents in marine sponges (e.g. *Stylissa carteri*), bryozoans, and cnidarians (Anjum et al., 2016; FAO, 2018), and anti-inflammatory and anti-bacterial effects of soft coral (Cheng et al., 2008).

The tourism industry in the recent past has been hit hard by mass coral bleaching impacts on coral reefs. The whitening of the reef and loss of live coral has major impacts ecologically and is probably one of the most aesthetically damaging consequences of climate change. The Great Barrier Reef (GBR), a popular tourist destination for divers and snorkelers alike for the great beauty of the reefs was labelled a “last chance tourism destination” since the major bleaching event in 2016 – 2017 which was widely documented in the media (Piggott-McKellar & McNamara, 2017). In combination with media reports and academic literature, reporting the bleaching event, major declines in tourism were reported. The tourism boards blamed academics for documenting the bleaching event as the cause of the bad image and reputation for the GBR (Remeikis, 2018), leading to declines in tourism revenue (Prideaux et al., 2018).

The coastal protection which coral reefs provide is, of course, of fundamental importance to coastal communities. With increasing risk to sea-level rise, tens of millions of peoples worldwide could be displaced (McLeman, 2018). A study by Simon et al. (2016) conducted in the Solomon Islands, a global sea-level rise hotspot, has documented that sea-level rise is already having major effects on the communities there. They found five vegetated islands have recently vanished and that shoreline recession has destroyed villages that have existed since 1935, leading to community relocation. However, even in less extreme cases, the increase in sea level coupled with the predicted changing frequency and severity of storms (Sainsbury et al., 2018) could have major impacts of society. Sea level rise could cause loss and damage of buildings and infrastructure, increase water level, therefore result in inundation more inland from hazards such as storms, tsunamis, and king tides (McLeman, 2018). This increase is surface water runoff, could then cause food and fresh-water security issues, if sea-water ruins crops and enters freshwater stores.

It is clear that climate change has detrimental impacts on the ecosystem, and therefore the human populations and communities that are dependent on them. However, as there can be great uncertainty around climate change and coral reef ecosystems, changes across the global distribution of coral reefs will vary (Wolff et al., 2015). Factors that will also be drivers in the influence of change to climate change can include, country development – more developed vs. less developed countries, with a particular focus on poverty. Climate change impacts can reinforce poverty cycles as some poorer communities have higher exposure and are more vulnerable with fewer coping capacities (Schaefer & Waters, 2016). Social class can affect the level of coping capacity of communities. For example, in Indonesia, Bajau communities (traditionally nomadic-sea faring communities) are perceived as a lower class than populations living on the main islands. This has restricted land ownership and therefore have restricted adaptive capacity for food security from alternative terrestrial food sources (Bene, 2017). Key challenges identified from a Sustainable Fisheries Livelihoods programme included rights and access allocation, corruption, lack of local financial, intellectual and innovative capacity and centralized governance (Ferrol-Schulte et al., 2013).

A study by Robinson et al. (2019), investigated the productive instability of coral reef fisheries after climate-driven regime shifts. They found that coral bleaching increased fishery dependence on herbivore species and stated that climate-impacted reefs can still provide livelihoods and protein for the human populations. Nevertheless, if this is true, the effect of targeting lower trophic species can have profound effects on the ecosystem functioning and resilience; this is an example of how human populations can positively adapt and cope to climate impacts but increases the negative disturbances to the ecosystem itself.

The complexity of coral reef ecosystems and interactions with associated human populations show that climate change adaptations and mitigation actions are more often than not, very difficult to get right.

Value of coral reefs

Valuing natural systems has been done through a number of methods by measuring the monetary value of the ecosystem services the coral reefs provide (Lum, 2006). Costanza et al. (1997) valued coral reefs at US\$1610 ($ha^{-1}yr^{-1}$)[1]; these estimates were based on 17 ecosystems services for 16 different biomes. Through a thorough literature review and synthesised information during a one-week workshop, they were able to gather estimates of ecosystem services for each biome. Each estimate was then converted into 1994 US\$ $ha^{-1}yr^{-1}$ using a USA consumer price index. This seminal paper kicked off over 20 years' of research into ecosystems services (Costanza et al., 2017). Constanza's research, alongside de Groot et al. (2012b) has shown progression in the valuation of ecosystem services across biomes, with more recent estimates of coral reefs valued at US\$9.9 trillion/yr^{-1} (Costanza et al., 2014). They also showed that from 1997 to the 2014 paper, there was a loss of US\$11.9 trillion/yr^{-1} in coral reefs, mainly due to a decrease in coral reef area and the changes in using 2011 \$ unit values. From the work of valuing natural systems using the services and goods provided by the ecosystem, researchers have heavily advised for these services and goods to not to be used as private commodities (Costanza et al., 2014). Although fish and provisioning services may enter the private market, it is a crucial perspective to note that the ecosystems producing them are common assets (Costanza et al., 2014).

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[1] Total value of ecosystem services in 1994 US$ per hectare per year.

Spalding et al. (2017) mapped the global value and distribution of coral reef tourism. They valued the global coral reef tourism at nearly US$36 billion/yr^{-1}; this covers 30% of the world’s reefs and equates to 9% of all coastal tourism values in the world’s coral reef countries. A similar study aimed to value the global flooding protection provided by coral reefs (Beck et al., 2018). They found that coral reefs (71,000km of coastlines, included in the study) reduced expected damages from storms by more than US$4 billion annually and flooding for up to 200,000 people. Without reefs (developed scenario for a 1 metre decrease in reef height for model for study) the expected damage would rise up to US$4.72 billion/yr^{-1}. They were able to identify where reefs provide the greatest flood protection services. Indonesia alone averts up to US$639 million of damages, equating to 0.04% of the country GDP. These two studies are a part of a wider project “Mapping Ocean Wealth” led by The Nature Conservancy in partnership with The World Bank. This project aims to value and map the varied ocean ecosystems by evaluating nature as an economic asset, producing quantitative and spatial information. This is to ensure that decisions and policies can be developed and more informed that leads to better planning, conservation and investment decisions.

Coral reef fisheries are considered an important commodity of coral reef ecosystems, evident in providing many livelihoods for the global community. Coral reef fisheries provide jobs and income for up to 6 million people (L. S. L. Teh et al., 2013). Additionally, the global value of fish and fish products exports in 2016 was at US$143 billion, in addition to US$1.7 billion for seaweeds and aquatic plants (57%), inedible fish by-products (32%) and sponges and corals (11%) (FAO, 2018). However, the true value of coral reef fisheries, like many fisheries is difficult due to underreporting of landings (Newton et al., 2007), or even no reporting at all in the case of many artisanal fishing practices.

Studies have been implemented to look at how damages from ship groundings and pollution are valued (Lum, 2006). One method resource managers and government lawyers have adopted was utilising an environmental damage recovery model, habitat equivalency analysis (HEA). The HEA has been used to evaluate the amount of restoration required to compensate for the loss of natural resources (Precht et al., 2002); additionally, the model adopts a discount rate to account for the fact that the ecosystem services gained from restoration will be less valuable than the original state of the service. This method was used to assess the economic impact of a Nuclear Submarine grounding in Florida and the subsequent potential restoration required in a study by Banks et al. (1998). The model inputs included the amount of damaged reef (area), the discount rate and the reef recovery rate. The total economic impact of the grounding was found to total US$2,394,947 (1995 values); the State of Florida filed a claim, against the US for US$2.4 million for the damages. This value translated to 2019 values would equate to US$3,972,343.33 of damage across 1205 m^2, ~US$3290/$m^2$. This was finally settled for $750,000 and a major proportion was designated to reef restoration.

Construction and maintenance of tropical breakwaters have been found to cost much higher rates per m^2 than coral reef restoration projects (Ferrario et al., 2014). Coral reef restoration projects aim to restore reefs to ‘healthy’ states in terms of coral cover that in turn provides significant coastal protection. Table 5, summarises the cost of some coral reef restoration projects and the techniques used. A successful large-scale coral reef rehabilitation project in Indonesia set out to restore areas of coral reefs that had been damaged by destructive blast fishing. They demonstrated using hexagonal-shaped steel structures called “spiders” could be a relatively low, US$24.85/$m^2$, economic coral reef restoration cost. They were able to restore 2 ha of reef with 0.7 ha of spiders, which increased live coral cover on from 7 – 8 % up to 48% after one year of deployment (Williams et al., 2019).

Table 5. Costs of coral reef restoration projects, adapted from Ferrario et al. (2014).

Restoration technique	Location	Year	Original cost ($ m^{-2})	2012 Unit cost* ($ m^{-2})	2019 Unit cost* ($ m^{-2})
Paving slabs + chain-link fencing	Maldives	1994	40	62	69.12
Armorflex	Maldives	1994	103	159	177.99
Armorflex + coral transplantation	Maldives	1994	151	233	260.93
Concrete Blocks	Maldives	1994	328	508	566.79
Concrete structures + coral transplantation	Florida	1991	550	927	1034.15
Concrete structures + coral transplantation	Florida	1994	10,000	15,500‡	17,280.16
Rock stabilization	Indonesia	2005	5	6	6.56
Reef Ball	Various	2005	40	47	52.45
EcoReef	Various	2005	70	82	91.79
Biorock	Various	2005	1.6–110	2–129	2.10 – 144.24
Spiders	Indonesia	2015	24.85	NA	26.85

*Project costs were adjusted from year of project completion to 2012 and 2019 US$ using the online inflation converter available at www.usinflationcalculator.com.

†Estimated cost per 1 m length of shoreline enhancement: 2012 Unit cost × 10; see Methods.

‡The costs of coral restoration alone were not published, hence this estimate also includes funding used for compensatory restoration and grounding prevention elsewhere in the Florida Keys National Marine Sanctuary.

Above are examples of where monetary value has been placed on coral reefs. Monetising natural assets, ecosystem services, and goods can also be termed “natural capital”. However, there is much difficulty in valuing ecosystem cultural services, as these often provide no material benefit. These cultural services, or non-material ecosystem services, are linked with our emotional perceptions of the world; which proves a real challenge to value. Examples include spiritual enrichment, cognitive development, recreation, and aesthetic experiences (Small et al., 2017).

The value of coral reef ecosystems are extremely high and are worth more intact and healthy, than degraded or lost completely. The worth of coral reefs is not just monetary, but the livelihoods and welfare provided by them are often irreplaceable. Where alternative livelihood initiatives can be questionable in their staying power and implementation. For example in the Philippines, seaweed farming promoted to relieve stress on fisheries, attracted migrants from other areas due to the economic opportunity offered consequently, resulting in more coastal fishers (J. Cinner, 2014). The development of natural capital and using monetary values, allow for ecosystems services and goods from ecosystems to be translated across sectors and understood in a world where value is often referenced to money. Monetary metrics aid the development of informed management and policymaking.

It is noteworthy to realise that many projects, research, and funding goes into the protection, conservation, restoration and management of coral reef ecosystems. The empirical facts that coral reefs are among the most fragile and critical ecosystems in the oceans and on the planet are continually being recognised (Hoegh-Guldberg et al., 2018; Pandolfi, 2015). However, the effort and strategies of protecting the reefs and the people from climate change, are ever requiring new and innovative ways to be truly effective in the short and long term.

Climate change insurance

Insurance can be a tool to help people manage and transfer risk effectively, in the context of climate change this is to ensure people become climate-resilient and have strategies to cope with potential loss from climate shocks (Schaefer & Waters, 2016). Climate change insurance can be used as a long-term solution to adapt to the effects of climate change and transfer risk to a third party e.g. insurance/reinsurance company (CCRIF, 2010). The insurer usually pays out claims from the policyholder pool to the few unfortunate policyholders that suffer losses (Collier, 2009). How premiums are calculated, can be problematic in terms of the scale the premium covers; i.e. climatic shocks can affect millions of people even on regional scales. Nevertheless, climate change insurance or climate risk insurance is at the forefront of the insurance industry agenda. In 2015 at a G7 summit in Berlin, a conference was held to discuss the introduction or augmentation of insurance solutions to developing and emerging countries (Munich Re, 2015). The report entitled *Ocean risk and the insurance industry,* by Niehörster and Murnane (2018) in partnership with insurance and reinsurance company XL Catlin; are pioneering the development of insurance policies, including calls for developing insurance solutions for marine ecosystem services in developing countries. Though this is namely in the interest of a business opportunity and to assist industry partners with climate risk, this could be applied in a similar way to general human populations. Prior to this the “Munich Climate Initiative” was formed in April 2005 as a response to insurance solutions as adaptation initiatives for climate change, and focusing on the poorest and most vulnerable people in developing countries (Munich Climate Insurance Initiative, 2005). A global fund, The Green Climate Fund, was set up in 2010 to support efforts of developing countries to respond to the challenge of climate change (Green Climate Fund, 2018). Additionally, in November 2017 the “InsuResilience” initiative was launched at COP23 in Bonn, which is a global partnership for climate and disaster risk finance and insurance solutions (InsuResilience, 2018).

The numerous funds and initiatives being launched across the insurance industry is an indication of the direction the industry is heading. The need and call for action, for global solutions against climate change and the use of insurance, are becoming more widely accepted. The use of insuring against ocean risk is creating emerging business opportunities within the Blue economy (Blue economy: industries that utilise the ecosystem services of the ocean) and the populations that rely on them (Niehörster & Murnane, 2018). However, there is still much research required to apply these solutions to the challenging scenarios that arise from the management of coral reef ecosystem services and their dependent human populations.

Climate insurance using the *public-private partnership* model, as the example developed by The Nature Conservancy in Mexico, could effectively build resilience (through setting aside a fund for maintenance and monitoring of ecosystems) in countries that are most exposed to risk and can be used as an adaptation strategy for active management of coral reef ecosystems (Niehörster & Murnane, 2018). This model may only be applicable where private stakeholders have an interest; which can prove difficult, particularly in very remote and/or extremely poor areas where there may be no presence of a private stakeholder. In these instances, sovereign insurance pools may be an alternative option in which insurance could be applied to more vulnerable people with lower coping capabilities. It has been argued that creating climate insurance policies could provide disincentives for risk reduction against climate change if not correctly structured (Surminski et al., 2016). The disincentives can manifest in communities/countries not applying actions into reducing carbon emissions and long-term conservation or management actions, then rely on the insurance premiums to assist with climate events when they happen. Climate change insurance is a tool that perhaps needs to be part of a wider strategy to prepare and protect against climate change rather than to be used in isolation or as an alternative solution to adaptation (Surminski et al., 2016).

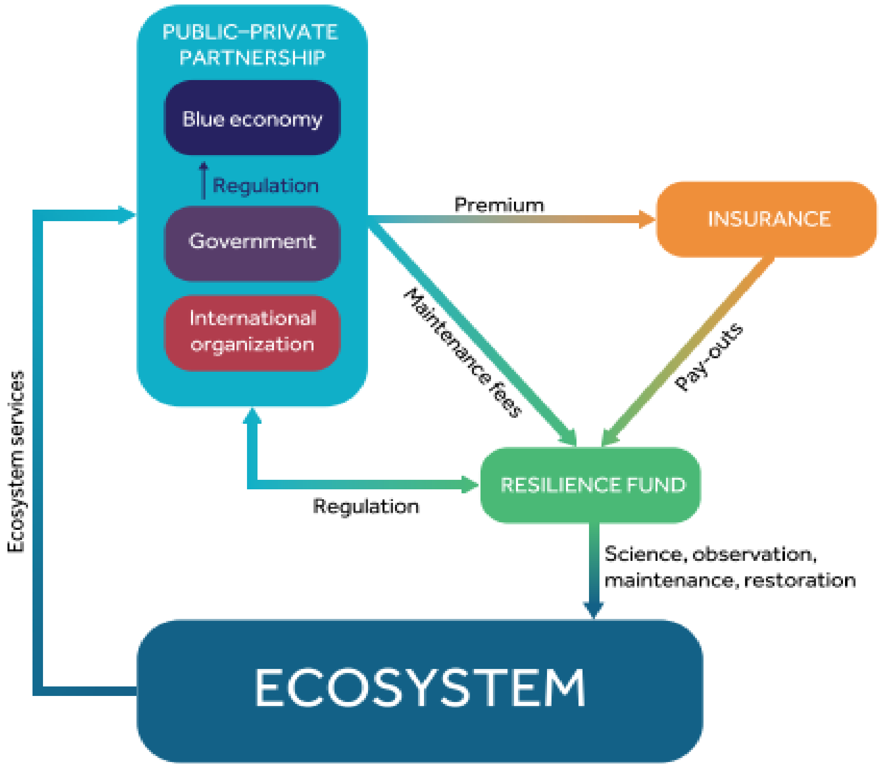

Figure 5. Possible structure of resilience funds in developing countries for sustainable ecosystem services and their insurance element. Taken from (Niehörster & Murnane, 2018).

The Mexican state, Quintana Roo insurance policy example is a parametric or index-based insurance policy, which is paid out when the parameter is triggered (Brown et al., 2011). The Coastal Zone Management Trust manages and buys the insurance policy, which is triggered by wind speed of over 100 knots, however, this does not cover other reef damage such as coral bleaching or algae overgrowth; pay-outs contribute towards restoring and protecting the reef and beaches (The Nature Conservancy, 2017). The details of how this policy was calculated is not known and is kept guarded by Swiss Re. More traditional insurance solutions could be applied, however, the payments will only be triggered through actual loss and damage of physical assets. Due to complex assessments, the claims process could take months or even years before payment is delivered (A. Martin, 2018). This could be a considerably less desirable option in the face of acute climate shocks that may require more immediate recovery action.

In a recent update, Munich Re has warned that climate change could make general insurance too expensive for people. They blamed global warming for the loss of up to US$24 billion caused by the California wildfires. If risk from natural hazards keeps increasing, then risk prices will have to adjust accordingly to keep insurance sustainable (Nelsen, 2019). This type of trend could likely follow into the reinsurance sector (insurance for insurers, whereby portions of the risk portfolio is transferred to third parties; Banton, 2019). How this will affect individuals and communities that require insurance to allow them to become resilient against climate change is yet to be seen.

More insurance policies have arisen since the conception of the Mexican insurance policy from The Nature Conservancy. For example, the Wildfire Resilience Insurance project based in California in partnership with Willis Towers Watson (The Nature Conservancy, 2021a) and the Missouri River Community Flood Resilience Insurance project in partnership with reinsurance company Munich Re (The Nature Conservancy, 2021b). A weather-based index insurance product was developed for fisherfolk to enhance resilience against climate-related disasters, by the “Caribbean Oceans and Aquaculture SusTainability Facility” (COAST), and was launched in Grenada and Saint Lucia in 2019 (*The Launch of COAST Fisheries Insurance*, 2019). The government purchases the COAST insurance policy and the beneficiaries are the those in the fisheries sector, when the policy is paid out due to weather-related events (World Bank, 2019). It is apparent that insurance can be a novel tool in climate resilience for both people and natural systems to extreme climatic events.

Conclusions

It is evident that there is plenty of data available and enough empirical evidence of climate change impacts on coral reefs and their dependent communities. Livelihoods, welfare and even alternative livelihoods are at stake in the face of global climate change. Mechanisms to help protect communities and ecosystems from climate change need reviewing and emerging and novel solutions are available in the form of insurance. However, there is a level of uncertainty in the future of coral reefs, and how insurance can capture whole communities and/or individuals especially those living in developing countries and have limited coping capacities.

The insurance industry is recognising the need for the development and implementation of climate insurance, however, initially this has been focused within the private sector. Research and development for insurance policies for emerging and poorer communities are in progress, with recent recognition being focused on ocean risk. Ocean and coral reef ecosystems pose a complex threat, with many cascading effects on local and global scales to community and business. Due to the broad ecological and social differences that are found across the global distribution of coral reefs we can be sure that risk and vulnerability varies across this spatial and temporal scales.

Within this thesis I aim to provide the relevant information to facilitate the development of dependency and risk models to be utilised in coral reef insurance, policy and conservation solutions, through (1) providing a comprehensive list of coral reef countries (2) updating recycled statistics of human populations near coral reefs (population size and location) and, (3) developing a conceptual framework for human dependency on coral reefs in order to redirect the thinking and methodology applied to human dependency calculations. These studies will be split into two data chapters (chapter 2: An assessment of people living by coral reefs over space and time and chapter 3: Rethinking assessment methods of human dependency on coral reef ecosystems); I believe it is best to keep the analyses and discussion of the large 'human populations by coral reefs' dataset into one large data chapter rather than split them over several smaller repetitive chapters. This will allow us to see global temporal trends in human populations near coral reefs, and how human dependency on coral reefs are defined and influenced in coral reef countries. The outputs of the project will form a long-term global dataset of which can be utilised by all coral reef researchers, policymakers and insurance companies. This collective approach has also facilitated the work being recently published in a well-respected journal – Global Change Biology. The second data chapter focuses on shifting perspectives about how human dependency on coral reefs is assessed.

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Chapter 2: An assessment of people living by coral reefs over space and time.

Abstract

Human populations near ecosystems are used as both a proxy for dependency on ecosystems, and conversely to estimate threats. For that reason, the number of people living near coral reefs is often used in regional coral reef management, evaluation of risk at regional and global scales, and even considerations of funding needs. Human populations, and their statistics, are ever-changing and data relating to coral reefs have not been updated regularly. Here we present an up-to-date analysis of the abundance and density of people living within 5-100 km of coral reef ecosystems using freely available datasets and replicable methods. We present trends of changes in human populations living near coral reefs over a 20-year time period (2000-2020), broken down by region and country, the proportion of population close to coral reefs, as well as by socio-economic denominations such as country income category and SIDS (Small Island Developing States). We find that across 117 coral reef countries there are currently close to a billion people living within 100 km of a coral reef (~13% of the global population) compared to 762 million people in 2000. Population growth by coral reefs is higher than global averages. The Indian Ocean saw a 33% increase in populations within 100 km of a coral reef and 71% at 5 km. In SIDS the proportion of the total population within 100 km of a coral reef is extremely high: 94% in 2020. Population density 5-10 km from coral reefs is 4x the global average. From 5-100 km, more people from lower-middle income countries live by coral reefs than any other income category. Our findings provide the most up-to-date and extensive statistics on the regional and nation-level differences in population trends that play a large role in coral reef health and survival.

Keywords: coral reefs, human population trends, coral reef management, global coral reefs assessment, sustainable development, marine conservation

Introduction

The global human population (therein called ‘population’) in 2020 stood at 7.76 billion people (The World Bank, 2022). Recent projections of population have shown that it could reach 10.9 billion people by 2100 (medium-variant projection); a projection lower than previous ones largely due to lower current and predicted fertility rates (United Nations, 2019). Global population growth peaked at 2.1 % per year from 1965 to 1970 and has now fallen to below 1.1 % per year from 2015 to 2020 (United Nations, 2019). However, populations are not distributed evenly across the globe and the heterogeneity of age-sex structure, education, and rural or urban factors heavily influence population projections (KC & Lutz, 2017).

Coastal zones are particularly important for human settlements and have been regarded as hot spots for habitation (Andrew et al., 2019a). A special IPCC report(Pörtner et al., 2019), estimated that 680 million people live in low-lying coastal zones and projected numbers to reach more than a billion by 2050. Proximity to coasts is essential for millions of people who rely upon this access for their livelihoods (Kummu et al., 2016). There is concern regarding high coastal zone population growth as it has been associated with the degradation of coastal and marine ecosystems (Creel, 2003). The population density in coastal areas is three times higher than the world's average population density, with increasing growth rates (Marone et al., 2017). Despite prevalent coastal hazards (Marone et al., 2017) nearly all coastal ecosystems were found to have net in-migration between 1970 and 2000 (Neumann et al., 2015a).

Of particular interest are Small Island Developing States (SIDS), where the dependency on marine ecosystems are particularly high. These populations are recognised as a special group of countries that are disproportionately vulnerable to climate change (S. ann Robinson, 2020). Many SIDS have vast coral reefs and have a particular dependency on the many critical ecosystem services and goods coral reefs provide (Harborne et al., 2017), from which people benefit both directly and indirectly. For example, coastal protection, water purification, recreation and tourism, source of animal protein, extraction of raw materials and, fisheries (Harborne et al., 2017; Moritz et al., 2017; Spalding et al., 2017). These widely recognised services provide livelihoods and welfare to the human populations which surround and utilise coral reefs globally (Frieler et al., 2013; Hughes, Barnes, et al., 2017; Ruppert et al., 2018).

Human populations and population growth have been consistently associated with negative impacts on coral reef fisheries, ecosystem function, and biodiversity (J. E. Cinner et al., 2020). This is supported by evidence that slower-growing human populations and reduced access to reefs by human settlements are associated with more abundant framework-building coral (Darling et al., 2019). There are direct human activities that also cause major loss of structural reef complexity, and consequently associated biodiversity, e.g. blast fishing (Harborne et al., 2017; Hoey & Bellwood, 2011). Coral cover decline and coral reefs are becoming increasingly modified, which are indirectly caused by the increased global population, and global GDP per capita (Bellwood et al., 2019). More elusively, the proximity of populations to coral reefs has caused changes to water quality either directly through nitrification (e.g. sewage input), or indirectly through coastal modification (e.g. removal of mangrove forest), and/or land management (changes to adjacent terrestrial vegetation e.g. conversion of forest to palm oil plantations), leading to high turbidity and sedimentation, and subsequent reductions in coral reef health (Ruppert et al., 2018).

The reduction and/or loss of coral reefs has not only detrimental effects on ecosystems, but also on the people that rely on them. Coral reefs are estimated to provide up to

$9.9 trillion/year through ecosystem services and goods (Costanza et al., 2014), with up to $36 billion from coral reef tourism (Spalding et al., 2017). Across three Southeast Asian countries (Indonesia, Thailand and Malaysia) alone, the scuba diving industry was estimated, pre-covid, to be around $4.5 billion/year (Pascoe et al., 2014). Additionally, it is found that coral reefs can provide up to $4 billion of savings in flood protection (Beck et al., 2018). It is evident that the economy of coral reef countries would be severely damaged by the degradation and loss of coral reefs (Schleussner et al., 2018). Subsequently, this will likely affect the income, employment, poverty levels, and food security of local populations as well as the appeal of coral reefs to tourists. Finally, the change of reef structure and/or coral species composition in a warming and acidifying ocean can increase the risk of diseases such as harmful algal blooms and ciguatera, with implications for human health and well-being (Hoegh-Guldberg, Poloczanska, et al., 2017).

Reef-building corals of shallow waters only persist within a narrow set of environmental conditions - the sunlit and alkaline waters along tropical coasts (Frieler et al., 2013). Coral reef cover is predicted to decline between 70-90 % in the next decade (Darling et al., 2019; Frieler et al., 2013; Hoegh-Guldberg et al., 2018), and up to 99 % if global warming reaches 2°C above pre-industrial levels (IPCC, 2018b). This will have a devastating effect on the diversity of coral reefs and their inhabitants, which predominantly rely upon the heterogeneity of reef-building corals in all their forms (Hoegh-Guldberg, Pendleton, et al., 2017). There are critical consequences for human communities of coral reef collapse; for example, increased risk of food poverty, economic losses, and reduced coastal protection from storms (Hoegh-Guldberg et al., 2019), to name a few.

Population is not only represented in terms of threats to ecosystems; Although there is a multifaceted interconnected link between coral reefs and human dependency, population is also often used as a proxy of human dependency on coral reefs (Andrello et al., 2022; Beck, 2014; Darling et al., 2019; Donner & Potere, 2007; Frieler et al., 2013; C. Wilkinson, 2004a). Additionally, distance from the coast is an important factor in understanding risks and/or dependency in these coastal populations (Andrew et al., 2019a). In terms of population and coral reefs, there is a lack of long-term data readily available. As there are increasing coastal populations, and impacts on coral reefs associated with increasing populations, it is important to have standardised and replicable global assessments of the number of people that live by coral reefs. Here we present an 20-year period of such data covering populations within 100 km (a distance considered the ‘coastal’ area from coastlines, and within which inhabitants are highly likely to be using marine ecosystems for food and livelihoods; (Burke et al., 2011b) of global coral reefs. It is the most comprehensive study of populations living near coral reefs, including, for the first time, all countries which border coral reefs (rather than a subset - previous “global” coral reef studies included varying numbers of countries, ranging from 40 to 108; Table 6). Trends of population change near coral reefs are investigated to provide insight into the potential future of the intimately intertwined story of human populations and coral reef ecosystems. This baseline assessment of populations near coral reefs provides coral reef scientists, policy decision-makers, and coral reef managers with a country-level and regional overview from 2000 to 2020; we also assess this change by country-level income classification and SIDS. Our analyses will support decision-making when addressing and distributing limited funds and resources, something crucial to achieving the UN Sustainability Development Goals (SDGs), in particular addressing SDG 14 Life Below Water, which highlights that a mere 1.2% of national research budgets are allocated to ocean sciences – our data also helps bridge the country-level data gap for addressing SDG 13 on Climate Action (Guterres, 2020), as well as creating novel climate adaptation plans to conserve and protect coral reefs and the human populations against climate change.

Table 6. Overview of global coral reef studies, with number of countries/territories and global reef area (km^2).

Year Published	Number of countries/territories included in the study	The global area of coral reefs (km^2)	Reef Area Calculation Method	Source
2001	80*	284,300^	Digitised reef maps (rounded to the nearest 100 km^2)	Spalding *et al.* (2001)
2004	96	284,803	Taken from Spalding *et al.* (2001), calculated from regional totals	Wilkinson (2004)
2008	95	284,803	Taken from Spalding *et al.* (2001), calculated from regional totals	Wilkinson (2008)
2011	108	250,000	Adapted with UNEP-WCMC Coral map	Burke *et al.* (2011)
2012	21	NA	NA	de Groot *et al.* (2012)
2013	98	NA	NA	Teh *et al.* (2013)
2016	101	NA	NA	Pendleton *et al.* (2016)
2017	102	249,423	Mapping Ocean Wealth Project: http://maps.oceanwealth.org	Spalding *et al.* (2017)
2018	40	NA	NA	Cinner *et al.* (2018)
2018	85*	152,478.6†	Sentinel-2 remote sensor images	Hedley *et al.* (2018)

*Listed countries included territories of grouped countries. NA – data not available or stated in the study. † Coral reef area covered by the Sentinel-2 data. ^Referred to as conservative estimate (Wilkinson, 2004)

Methodology

Data collection and manipulation

Coral reef countries were obtained from literature and compiled as a comprehensive dataset defined by countries within a 100 km radius of coral reefs. The maximum distance of extraction was defined as 100 km as this is the distance from the sea where populations are classed as coastal (Andrew et al., 2019a), additionally, populations within this area are more likely to derive or depend on coral reefs for their livelihoods and food reliance (Burke et al., 2011b). With the minimum distance of extraction at 5 km, this range was chosen to encompass differing mechanisms of dependency, risk and/or threats from coral reefs, such as subsistence fishing at the small buffer range and potential market effects at the larger buffer range. Country ocean regions were adapted from Reefs at Risk Revisited (Burke et al., 2011b) - Atlantic, Australia, Caribbean, Indian Ocean, Middle East, and Southeast Asia, with Australia being classed as a region in addition to a country. Additionally, the Caribbean was incorporated to encompass countries in the Caribbean that have coastlines both in the Atlantic and Pacific.

The United States, though one country, has four states in which coral reef buffers at 100 km are encompassed - these are Florida, Hawaii, Arizona, and California; Florida was classified under the Atlantic region, with Hawaii, Arizona, and California classified under the Pacific region.

Small Island Developing States (SIDS) were defined by the United Nations country classification, with a total of 38 UN members and 20 non-UN members (United Nations, 2020); Figure 5c). Country income group classifications were defined using the four(The World Bank, 2018) categories: low, lower-middle, upper-middle, and high.

Population statistics for each coral reef country were extracted from LandScan datasets; a comprehensive list is provided in Appendix I, including information on the region, sovereignty, ISO3, and ISO2 codes (The World Bank, 2018; United Nations, 2020). Coral country spatial data was obtained from the world dataset from the GADM database (Lloyd et al., 2017) and imported into R for further analysis.

The global distribution of coral reefs was obtained from the latest coral reef map provided by (UNEP-WCMC et al., 2018) v.4.

Global population distribution data were obtained from the LandScan datasets provided by Oak Ridge National Laboratory. The datasets are at approximately 1 km (30″ X 30″) spatial resolution and represent an ambient population (average over 24 hours) distribution (Bhaduri et al., 2002). LandScan data from 2000 to 2018 were downloaded from the LandScan website.

Data analysis

All data extractions, analyses, and mapping were done in the open-source software R v.3.6.0 (R Core Team, 2019).

Population statistics

The total populations near coral reefs were extracted from LandScan (Bhaduri et al., 2002) datasets for the years 2000 to 2020. Distance from reef was classified into 5 distance categories: 5 km, 10 km, 30 km, 50 km, and 100 km adapted from (Burke et al., 2011b) and (Andrew et al., 2019a). Spatial buffers of coral reefs were created for each distance category (Figure 7). The buffers were used to extract the total population of each coral reef country, within each distance category, and across time from the LandScan datasets. Additionally, country polygons were used to extract the entire country population to allow further analyses.

Population growth of coral reef countries was obtained from The World Bank repository (The World Bank, 2018); these reflect the whole country (e.g. the USA). The proportion of the total country population living near coral reefs was calculated, in addition to the yearly percentage population change and average population growth. Percentage change was compared to country population growth. LandScan does not recommend using their datasets for change detection, particularly on a cell-by-cell comparison (Bhaduri et al., 2002), however, our study aggregates population data to broad country scales (Table S1) which buffers against changes in Landscan over that time and Landscan has been found to be accurate when compared to other geographical estimates of population (Hall et al., 2012). The area of distance categories within each country was calculated, in addition to the entire country area, in km^2. Population density was then calculated for each country across distance categories and years. This was repeated on a global, regional (Figure 6a), and country-level, with additional groupings of income group (Figure 6b) and SIDS (Figure 6c). Regions were adapted from (Burke et al., 2011b), with the Caribbean sub-group created for this study instead of split into Atlantic and Pacific groupings due to the nature of the population data, and country-level analyses. Any country/territory that had available data on income group was included for analysis; those with no income group classification were listed as “others”. SIDS were analysed as a group; this included UN and non-UN members. A few countries were treated differently in the population analysis due to the lack of data and the nature of the data sources (Chapter 2 SI).

R workflow: Population Extraction

Points and polygons of global coral reef distribution spatial data (UNEP-WCMC) were summarised by country. For coral reef point and polygon data a custom function was created to project each country grouped points or polygons to a Lambert Azimuthal

Equal-Area projection based on the centroid of grouped points or polygons. Buffers were created on the country-based projected data to reduce distortion. Buffers were created from coral reef points and polygons at distances of 5, 10, 30, 50, and 100 km. Distance buffers were then cleaned for merging, ensuring intersections and overlapping data were cropped without losing information, and then finally merged into one dataset. Buffers were then re-projected to a global projection for WGS84 ESPG = 4326 and merged to create a global buffer of coral reef data for each distance category. Buffers that crossed the dateline were cleaned to ensure there was no overlap in future analysis, and were then mapped properly. The buffer data was combined with world (GADM) data with country and ISO3 attributes; this allowed the dissolution of segmented polygons within each country to create clean buffers by country (data available on GitHub – **https://github.com/amysw13/human_populations_by_coral_reefs**). Area in km^2 was calculated for all distance categories in each country. Additionally, entire country area was calculated using the world data polygons for each country. Cleaned buffer data for each distance category was used to extract population data from Landscan datasets using the extract function in the “velox” v.0.2.0 package (Hunziker, 2017) in R. Extractions were repeated for all distance categories and Landscan data between the years of 2000 and 2020. Maps were created using “ggplot2” package (Wickham, 2016) in R.

Maps

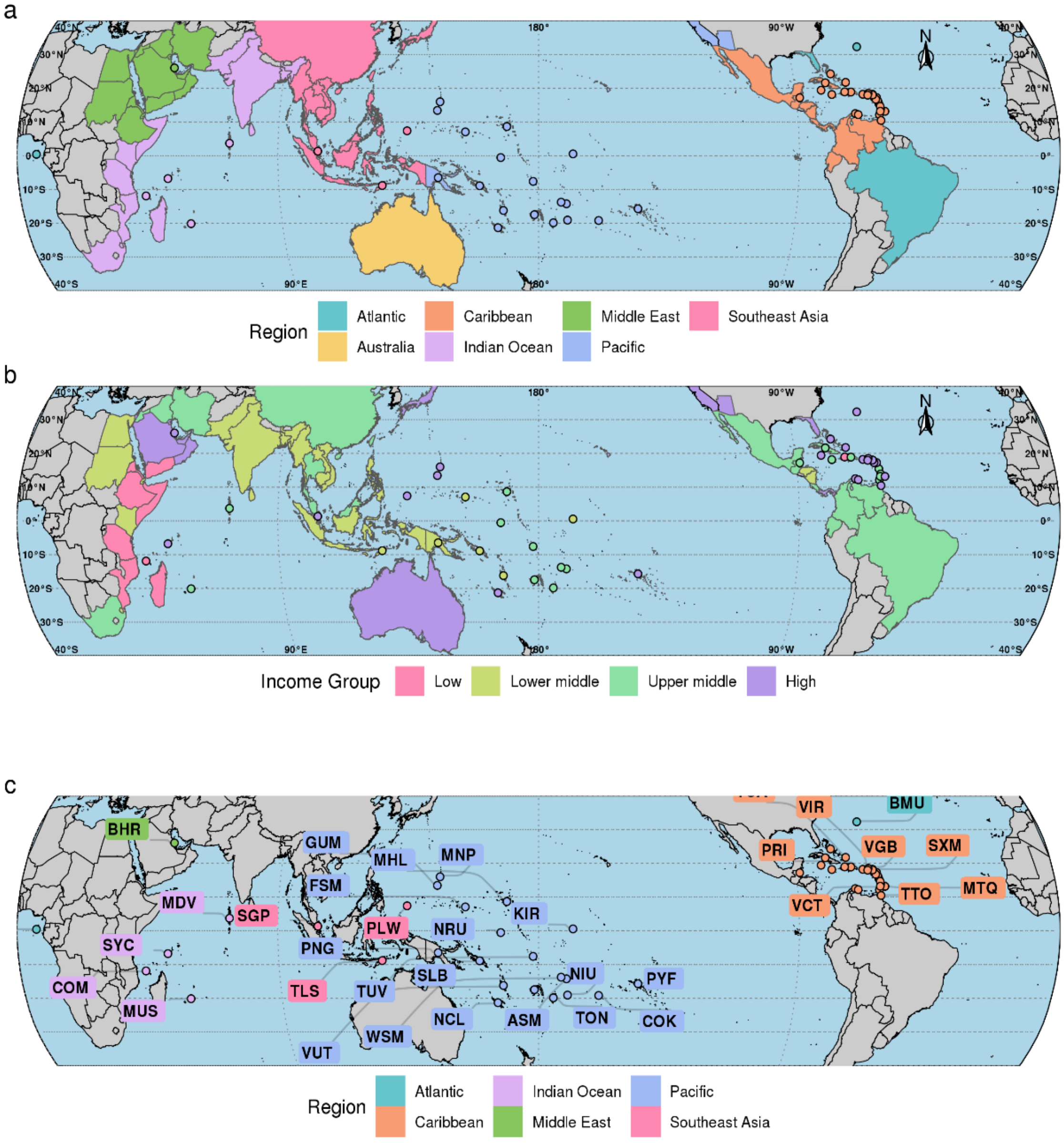

Figure 6. Coral reef countries (a) coloured by regional groupings, (b) coloured by Income Groupings and, (c) Small Island Developing States classified Coral reef countries, coloured by regional groupings, labelled with country ISO3 code (see Table S3 for country names and corresponding ISO3 codes). Points highlighting small island countries.

Distance buffers map

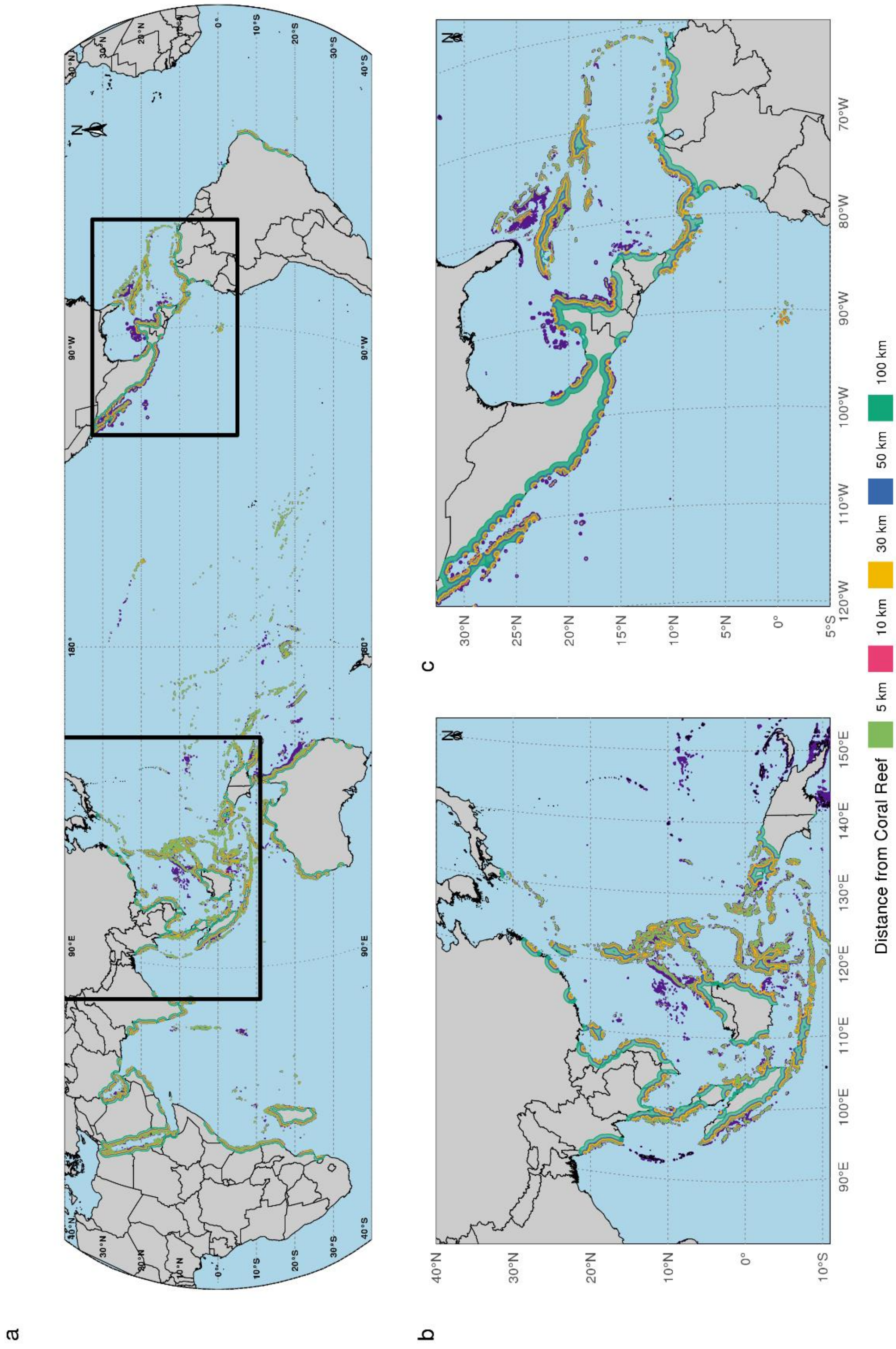

Figure 7. Map of buffers created around the (a) global distribution, (b) Southeast Asia and, (c) Caribbean regions of coral reefs (purple) at 5 km, 10 km, 30 km, 50 km, and, 100 km.

Results

Coral Reef Countries

There are 128 countries that are bordered by coral reefs or have coral reefs in their adjacent (100 km) waters. Four landlocked countries fell within 100 km of coral reefs (Table S9). Global coral cover was found to be 151,390.25 km^2, calculated from the UNEP-WCMC coral distribution spatial layer (UNEP-WCMC et al., 2018). A recent study generated a global coral reef probability map using convolutional neural networks and estimated the extent of global coral reefs to be 301,110 km^2 at a lower probability threshold of 60 % and 154,049 km^2 at the upper threshold of 65% (Li et al., 2020); our area estimations therefore appear to be at the lower range within literature (Spalding et al., 2001).

On a country level, Australia contains the largest area of coral reefs at 31,688.43 km^2 (20.93% of all coral reefs) followed by Indonesia and the Philippines with 20,233.23 km^2 (13.36%) and 13,573.40 km^2 (8.97%) respectively (full country rankings of global proportion of coral reefs and coral reef area in Table S14).

At 5 km there were a minimum of 109, and up to 117 coral reef countries at 100 km included in global population analyses (Table S11); variation was due to LandScan data updates over time which includes updated administrative borders. At regional levels in the Atlantic and Australia there are just 3 coral reef countries across all distances and over the years considered here Coral reef countries in the Caribbean (38), Indian Ocean (14 – 17), Middle East (14 – 16), Pacific (22 - 23) and Southeast Asia (15 - 19) varied over time and across distance from coral reefs (Table S12).

Across income groups, total coral reef countries included in the population analysis ranged from 94 to 101 over time and across distances from coral reefs. In low income groups between 8 – 9, lower-middle income groups 19 – 23, upper-middle income groups 31 – 32 and, high income groups 36 – 37 coral reef countries (Table S13). Out of a total of 58 SIDS on the UN list, 54 are coral reef countries (Table S10), with a total of 53 SIDS included in this study (as coral reefs in São Tomé and Príncipe are not mapped).

Populations near coral reefs

Global Population

Overall, total populations near coral reefs have increased steadily over time across all distance categories (Figure 8b). Populations within 100 km of coral reefs expanded from 762 million people in 2000 to 997 million people in 2020 (Figure 8b); this equates to 12.56% and 12.84% of the global population respectively (Figure 8a). There is a larger increase in populations living very close to coral reefs, with a 42.17% increase in population within 5 km of coral reefs from 2000 to 2020 compared to a 30.77% increase in populations within 100 km of coral reefs (Table S15); At 5 km from coral reefs population expanded from 76 million people in 2000 to 108 million people in 2020 (1.25% and 1.39% of the global population respectively).

The global population density of coral reef countries are generally lower the further away from coral reefs (Figure 8c). However, the highest population densities are found within 5 and 10 km from coral reefs, at 261 and 253 people per km^2 respectively in 2020. This is much higher than the average world population density of 60 people per km^2 (Table S15).

Average population growth of populations within 5 km to 100 km of coral reefs between 2000 and 2020 was found to be higher than the overall world population growth in 2000 and 2020 (Table S15). The average population growth between 2000-2020 was highest at 5 km at 1.78%, and at 100 km population growth was 1.35%. Overall, population growth near coral reefs was found to be higher than annual world population growth across all distances over the 20-year study period (Figure S14).

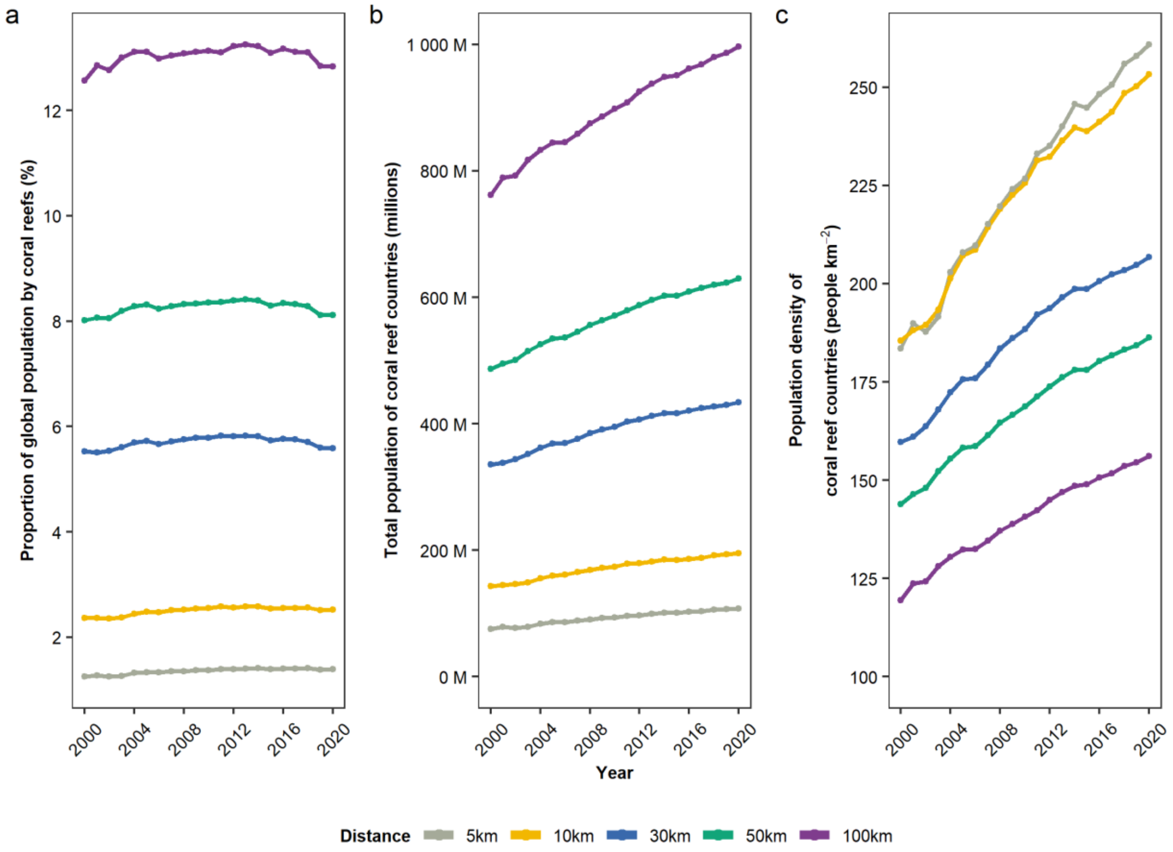

Figure 8. Global population proportion (%) (a), total population (b) and, population density (c) of people living within 5 km, 10 km, 30 km, 50 km, and 100 km from coral reefs between 2000 to 2020.

Regional Populations

Compared to all other regions, and across all distance categories, in line with findings from the Reefs at Risk Revisited report (Burke et al., 2011b), Southeast Asia contributes significantly to the global population living by coral reefs (

Figure 9b). This is followed by the Indian Ocean and the Caribbean. All regions had increased populations from 2000 to 2020 at 5 km and 100 km.

Error! Reference source not found. presents the summary of regional statistics at the closest coral reef buffer of 5 km and the most expansive buffer of 100 km from 2000 and 2020. At 100 km in 2020, Australia and the Caribbean have the highest regional proportion of population living by coral reefs compared to the entire regional coral population, at 37.10% and 35.86%. At 10 km human populations in the Pacific have the highest population proportion by coral reefs at 47.47% in 2020 however, this is also the lowest total population at 5.37 million people within 10 km of coral reefs. The most populous region in 2020 was Southeast Asia, with 558.05 million people 100 km from coral reefs, however, this equates to 25.31% of the regional population proportion.

The Middle East had a dramatic increase in the % of population increase from 2000 to 2020, with an 78.75% rise at 5 km and a 78.74% rise at 100 km. This is with an average population growth of 3.06% and 3% respectively. This peaked at 30 km with average population growth exceeding 3.3% from 2000 to 2020. The Atlantic was revealed to have extremely high population densities at 5 km in 2020, with 1104 people per km^2, followed by the Indian Ocean at approximately half that value at 562 people per km^2. At 100 km from coral reefs, the population density was still found to be relatively high at 272 people per km^2 in Southeast Asia and 216 people per km^2 in the Indian Ocean.

More detailed regional information is available in Table S16.

Table 7. Summary of regional populations statistics at 5 km and 100 km from 2000 and 2020 (all distances available in Table S16).

Region	**Distance from Coral Reefs**	**Coral Population (millions)**		**Proportion of Coral Population to Total regional Population (%)**		**Percentage increase in Coral Population (2000 - 2020)**	**Average Coral Population Growth (%, 2000 - 2020)**	**Coral Population Density (per km^2)**	
		2000	**2020**	**2000**	**2020**			**2000**	**2020**
Atlantic	**5 km**	3.89	4.86	2.07	2.09	25.09	1.14	883	1104
	100 km	21.59	28.69	11.47	12.35	32.89	1.47	118	157
Australia	**5 km**	0.22	0.31	1.14	1.21	40.08	2.88	13	19
	100 km	6.03	9.33	31.64	37.10	54.61	2.23	10	15
Caribbean	**5 km**	12.15	15.67	5.02	5.12	29.01	1.29	228	294
	100 km	90.06	109.86	37.18	35.86	21.98	1.00	73	89
Indian Ocean	**5 km**	12.31	21.06	1.04	1.33	71.05	2.77	329	562
	100 km	162.67	215.77	11.17	12.31	32.65	1.44	163	216
Middle East	**5 km**	5.21	9.31	2.31	2.69	78.75	3.06	153	273
	100 km	35.71	63.83	11.40	12.95	78.74	3.00	37	66
Pacific	**5 km**	3.35	4.37	39.55	38.38	30.38	1.36	46	60
	100 km	8.87	10.97	18.68	18.87	23.73	1.07	27	34
Southeast Asia	**5 km**	38.72	52.25	2.00	2.38	34.93	1.53	199	268
	100 km	437.12	558.05	22.50	25.31	27.66	1.24	213	272

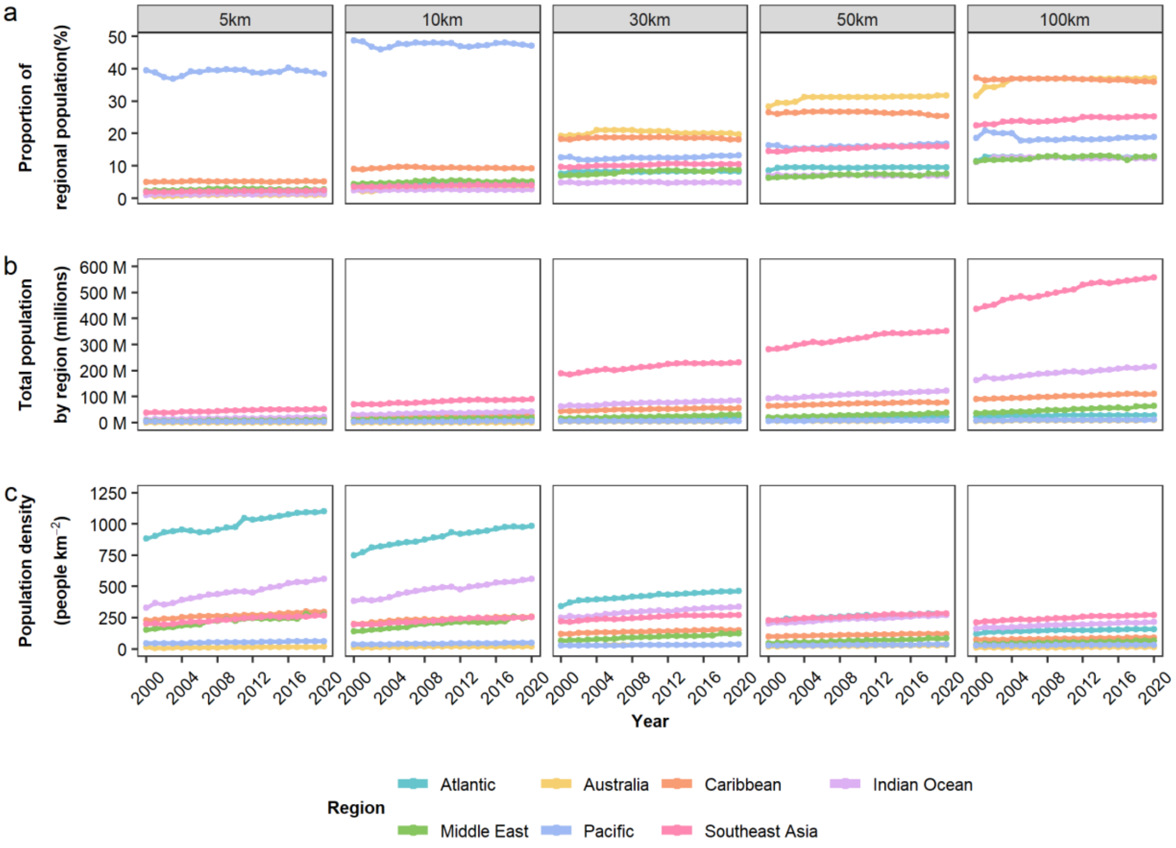

Figure 9. Regional population proportion of coral reef countries (%) (a), total population of coral reef countries by region (b) and, population density of coral reef countries by region (c) of people living within 5 km, 10 km, 30 km, 50 km, and 100 km from coral reefs between 2000 to 2020.

Income Groups

Compared to all other income groups, and across all distance categories, lower-middle income coral reef countries form the majority of the total global population living by coral reefs (Figure 10b). Low income group countries have the highest population proportion between 5 to 10 km, with high income groups overtaking at 30 km (Figure 10b). Low income group population proportions fell at 50 km with high income group countries increasing steadily from 2000 to 2020. Lower-middle and high income groups contributing increasingly higher proportions at 100 km (Figure 10a) with low income countries seeing a decrease from 2017. Upper-middle income groups had the lowest population proportions close to coral reefs, across all distances.

474.30 million people from lower-middle income countries lived within 100 km of a coral reef in 2000, 591.60 million people in 2020, equating to a 24.73% increase (Table S17). The percentage of people in lower-middle income countries living within 5 km of a coral reef has increased from 2000 (44.06 million people) to 2020 (60.24 million people); a 36.72% increase. There were 42.44 million people in 2000 and 67.16 million people in 2020 living within 100 km of a coral reef in low income countries; a 58.24% increase. Within 5 km there were 7.92 million people in 2000 and 15 million people in 2020, and although not as numerous as other income groups, this does equate to a dramatic 89.40% increase in population over 20 years and this peaked at 10 km with a 91.55% increase in population (Table S17).

In upper-middle income countries, there was a 35.40% increase in populations living within 100km of a coral reef (252.96 million people in 2020); There was an even sharper increase in populations within 5 km between 2000 (12.78 million people) and 2020 (18.23 million people), equating to a 42.69% increase. Whereas, high income countries at 100 km saw a 45.23% increase to 82.92 million people in 2020; and, at 5 km there was a 31.03% increase to 13.44 million people in 2020.

Population density across all income groups decreased as the distance from coral reefs increased (Figure 10c). Between 30 to 100 km, lower-middle, followed by upper-middle countries have higher population densities. Low income countries have greater variability of population density between distance categories over time compared to all other income groups. Population densities within 5 and 10 km of coral reefs in low income countries increases exponentially from 2000 to 2020. Low income country population density at 5 km in 2000 was 227 people per km^2, in 2020 this rose to 429 people per km^2, an 89.4% increase. Lower-middle income country population density remained relatively stable across distance categories. High income country population density was highest at 5 and 10 km and decreased from 30 to 100 km from coral reefs.

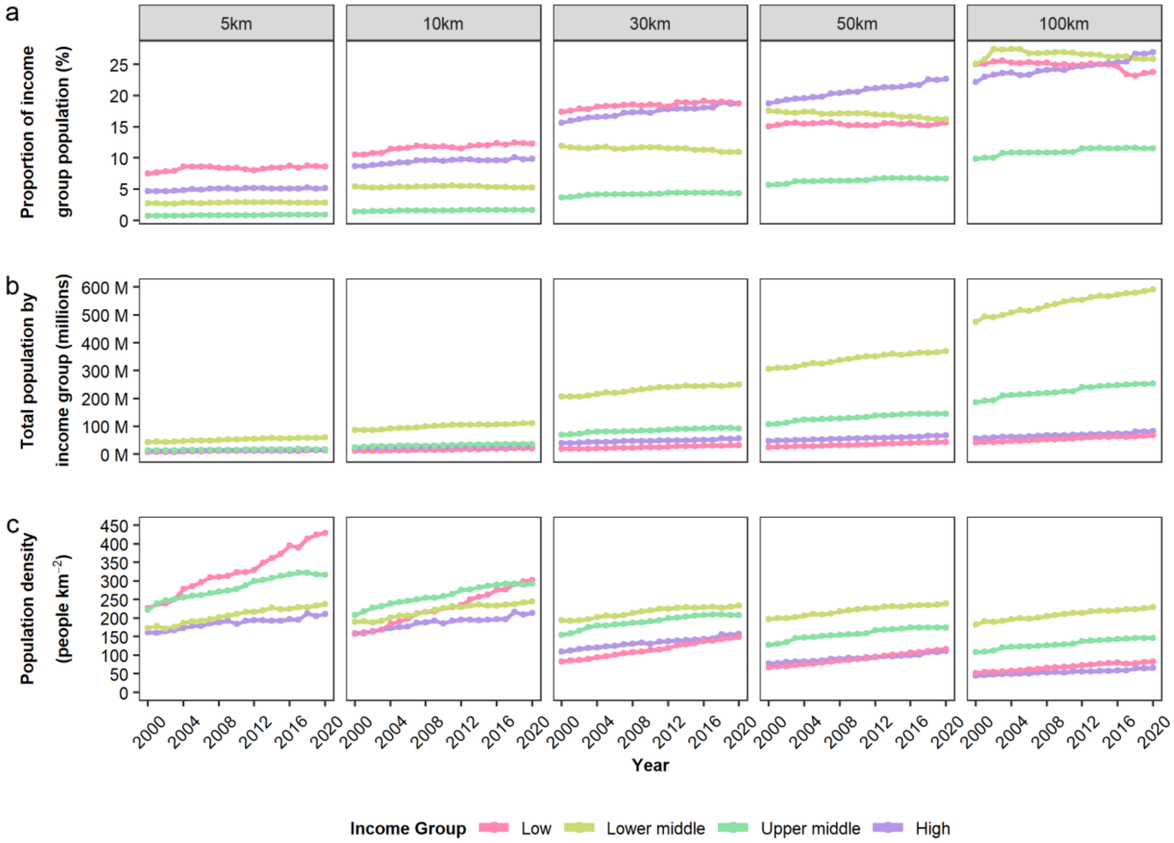

Figure 10. Income Group population proportion (%) (a), total population (b) and, population density (c) of people living within 5 km, 10 km, 30 km, 50 km, and 100 km from coral reefs between 2000 to 2020.

Small Island Developing States (SIDS)

SIDS total population increased slowly over time across all distances from coral reefs, with a notable decrease at 50 km from 2017 to 2018 (

Figure 11b); This seems to be due to SIDS generally being smaller by area making them more sensitive to changes in the Landscan population data. The proportion of the population living by a coral reef remained relatively stable across all distance categories over time (

Figure 11a).

There was a clear rise of 35.85% of the population living within 5 km of a coral reef in SIDS between 2000 (14.09 million people) and 2020 (18.86 million people; Table S18). The proportion of the total SIDS population within 100 km of a coral reef is very high, 94.02% in 2020; 47.4% of the population lived within 10 km of a coral reef in 2020.

Population density across SIDS in 2020 ranged from the lowest at 100 km at 103 people per km^2 to and highest at 5 km with 169 people per km^2. However, over time population density has generally increased across all distances with a greater change in populations at 5 km (

Figure 11c), notably from 2014 when population density at 5 km became higher than populations at 10 km.

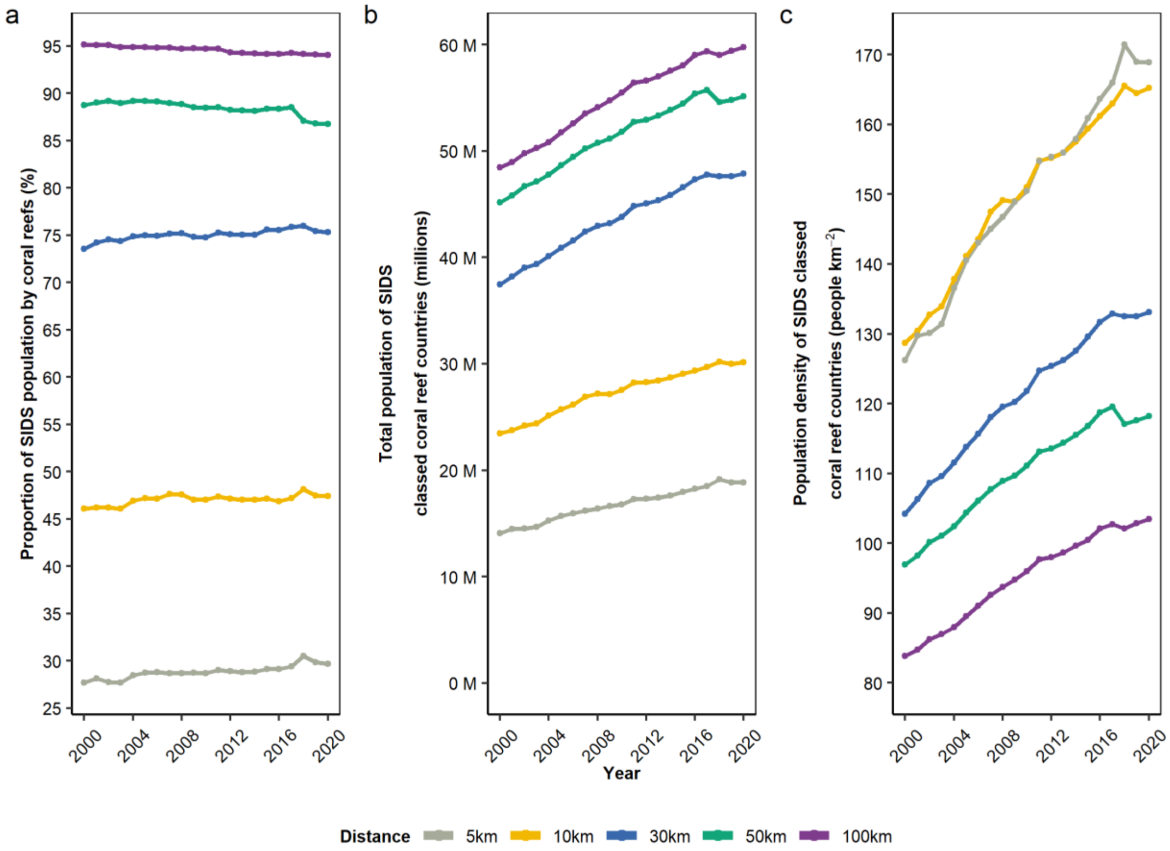

Figure 11. Small Island Developing States population proportion (%) (a), total population (b) and, population density (c) of people living within 5 km, 10 km, 30 km, 50 km, and 100 km from coral reefs between 2000 to 2020.

Country Insights

Across income groups, there are 2 low, 7 lower-middle, 15 upper-middle, 25 high income and 11 undefined income group countries with 100% of their population within 100 km of coral reefs. Out of the 53 SIDS included in this study, 47 have 100% of the population within 100 km of coral reefs.

There are a total of 60 countries which have 100% of their population within 100 km of coral reefs (Table S19), with 20 out of 60 that are within 5 km from coral reefs; these include countries such as Aruba, American Samoa, and Kiribati, and 17 out of 20 are classified as SIDS.

The Philippines and Indonesia consistently had the highest total population living within 5 - 50 km of a coral reef (Figure S12); India has the next highest total population within 5 and 10 km of a coral reef, with Haiti, ranked 5th when considering 5 km from coral reefs in 2018 (Figure S12a). Indonesia, the Philippines, and India were ranked 1st, 2nd and 3rd for the total population that lives within 30 to 50 km of a coral reef (Figure S12c & d).

Over time there has been variability in the ranking of countries with the highest population densities by coral reefs; in particular for population densities within 5 and 30 km of coral reefs (Figure S13a & c). When considering population densities within 5 km of a coral reef Bahrain ranked the highest in 2020, followed by the United Arab Emirates. Bahrain ranked top 5 for population density by coral reefs across all distance categories; Singapore and Jordon rank 4th and 5th respectively at 5 km from coral reefs. Kuwait ranked 3rd and 2nd for population density by coral reefs at 5 and 10 km respectively, and Singapore ranked 1st at 10 to 50 km (Figure S13a & b).

Discussion

Globally 997 million people are living within 100 km of a coral reef ecosystem across the 117 coral reef countries included in this analysis. This number is 147 million higher than previous estimations of the number of people that rely on coral reefs through proximity (850 million people, which was estimated using LandScan 2007 data; (Burke et al., 2011b). In 2020, within 30 km of coral reefs, there were 433.88 million people across 112 coral reef countries, 108 million of whom lived within 5 km of a coral reef where they are highly likely to be intimately dependent on coral reef ecosystems either indirectly or directly.

The proportion of people living near coral reefs has remained relatively stable over time and in 2020 around 13% of the global population was living within 100 km of coral reefs. Populations living by coral reefs had higher population growth and density than the global average and generic coastal population trends (Barbier, 2014c; Creel, 2003; Neumann et al., 2015a; The World Bank, 2018). Coral reef population density was 4 times higher between 5 to 10 km from coral reefs compared to the global average; Between 30 to 100 km from coral reef population density was around 3 times higher than the global average, equal to coastal population (populations within 100 km of coastlines) densities (Barbier, 2014a).

Unsurprisingly trends in the number of people living by coral reefs mirror many coastal population trends. Global population trends are projected to flatten towards the end of the century, however, coastal trends are predicted to continue to increase (Neumann et al., 2015a). As population growth by coral reefs outpaces that of broader coastal communities, when not considering assumptions of social factors such as migrations, displacement, and lifestyle changes (as these analyses do not), it is likely that coral reef populations will have even higher rates to that of coastal populations.

Considering populations close to coral reefs, Southeast Asia is the most populous region across time with 558.05 million people within 100 km in 2020, contributing to over half the global coral reef population; this region alone has more people living by coral reefs than the highly quoted statistic of 500 million people relying on coral reefs (C. Wilkinson, 2004a).

The Pacific had the highest population proportion living from 5 to 10 km of a coral reef. Notably, the highest proportion of people living within 5 km was among the Pacific coral reef countries and nearly half the population was found within 10 km. Being island nations the characteristics of small country size and remote location lend them to high populations close to coral reefs; our results align with a study by (Andrew et al., 2019a) which found entire populations within 5 km of coasts that included Kiribati, Nauru, American Samoa and Niue to name a few. This highlights that whole nations are vulnerable to climate change on coral reefs.

Corals found in the Arabian Gulf and the northern Red Sea are of particular importance due to stress resistance, with reefs potentially acting as marine refuges from climate change (Burt, 2014; Kleinhaus et al., 2020; Osman et al., 2018). The Middle East has the highest average population growth rate, which coincides with megadevelopments that have taken place in the Arabian Gulf, where economic diversification away from oil and towards tourism began in the 2000s (Burt & Bartholomew, 2019a).

Regional population density was extremely high in the Atlantic between 5 to 10 km from coral reefs. This region encompasses 3 coral reef countries; Brazil, Bermuda and the state of Florida in the USA (Figure S18f). The high population density in this region is likely driven by the close proximity of large cities to reefs and the unique formations and characteristics of these reefs. The Florida Keys reef tract hosts the third largest reef system in the world (Toth et al., 2018), with 5 counties in Southeast Florida that border these reefs having populations greater than 31 other USA states combined (Towle et al., 2020). Bermuda's unique reef tract and atoll-like formation have one of the highest population densities in the world (Coates et al., 2013). Brazilian reefs stretch over 3000 km of the coast and consist of shallow bank reefs that are attached to the coast, fringing reefs that border islands, and coral pinnacles known as "chapeirões" (Leão et al., 2016). The majority of cities in Brazil are located along the coast and have faced extreme rates of growth of more than 1000 % in recent decades (Leão et al., 2016).

Populations and industries that are dependent on climate-sensitive ecosystems are particularly vulnerable to direct risk to life and infrastructure, and indirect risk from loss of vital ecosystem services (Marshall et al., 2013). A study by (Herold et al., 2017) found that over the past two decades low income countries are facing more occurrences of temperature extremes than that of high income countries. This coupled with contributing the least to global gas emissions highlights the inequity of climate change impacts across the globe.

Low income coral reef countries are mainly found in the Indian Ocean and the Middle East; with Haiti in the Caribbean. Many of these countries can also be described as 'least developed' countries and are extremely vulnerable to acute external economic shocks, natural, and man-made disasters (UNFPA, 2012). Population estimates in these countries could be underestimated due to the way LandScan data is collected (Dobson et al., 2000), with lower estimates in rural areas (Aubrecht et al., 2015;

Gunasekera et al., 2015). We found that low income coral reef countries had great variability of population density, with overall population density within 5 and 10 km of a coral reef increasing exponentially from 2000 to 2018; with an 89.4% increase in total population from 2000 to 2020 at 5 km. Low income groups display the largest proportion of the population living between 5 to 30 km of coral reefs compared to the other income groups. Less than 10% of the population proportion contributes to the most densely populated areas at 5 km from coral reefs in low income groups; This could be a display of high dependency on coastal and/or marine resources which would cause populations to cluster around the coast.

Lower-middle income coral reef countries account for the most populous income group across all distances as Indonesia and the Philippines fall within this category. Much of Southeast Asian and Indian Ocean coral reefs are surrounded by lower-middle income coral reef countries. Lower-middle income countries are not as well-studied compared to low income countries and if mentioned are often grouped with low income countries. (Selig et al., 2018), ranked Indonesia as the most dependent country on marine ecosystems globally, followed by the Philippines.

SIDS are groups of developing countries that face similar social, economic, and environmental challenges (UN-OHRLLS, 2017); they are characterised by their small size, the concentration of infrastructure, limited resources, isolation from markets, economy, and population in coastal zones, which makes them highly vulnerable to climate hazards (S. ann Robinson, 2020; Schleussner et al., 2018). We found that in 2020 SIDS coral reef countries had 94.02% of their populations within 100 km of coral reefs.

Overall, 60 countries (of the 117 total coral reef countries included in this study) have 100% of their populations living within 100 km of coral reefs. If dependency on coral reefs is high (as is often the case in many tropical coastal societies(J. Cinner, 2014) coupled with low adaptive capacity against climate hazards, for example, Haiti and Saba (Siegel et al., 2019) and Vanuatu (Hafezi et al., 2020), populations are exposed to high levels of vulnerability to changes in coral reef ecosystems. Our study highlights the millions of people that have a potential dependency on coral reefs and are thus vulnerable to climate-change impacts on these sensitive ecosystems. We show that up to 500 million people in low income countries will need proactive adaptation strategies against climate change and highlight the double threat these communities face in terms of climate-sensitive ecosystems and low adaptive potential communities.

The distribution of the nearly one billion people that we consider coral reef populations are heterogeneous. We are able to indicate highly populated regions such as Southeast Asia and the extremely densely populated Atlantic region. If coral reefs and climate change remain on the current trajectory, populations by coral reefs will likely be negatively affected and vulnerable countries and regions will bear the burden of climate impacts (Schleussner et al., 2018). Understanding and effectively monitoring basic population statistics over time and distances from coral reefs and the dynamics of population changes helps identify those at comparatively higher risk making it a powerful management tool – something crucial for securing the future of our vulnerable coral reef ecosystems and the billion humans who rely on them. Such information allows governments and donors to efficiently quantify populations at risk, allocate financial resources, plan interventions (Palacios-Lopez et al., 2019a), and formulate mitigation strategies against hazards. This could range from having human-ecosystem-related policies, climate change mitigation plans, future models of coastal risk, and even contributing to the development of insuring ecosystems as natural assets. Our outputs will prove useful, not only to coral reef scientists and managers but to governments and councils, national and international policymakers, as well as science communicators.

Limitations of study

As with all global analyses, this study was limited to the accuracy of the spatial distribution of coral reefs from the UNEP-WCMC global coral reef distribution map and Landscan data. Additionally, we took population extractions from buffers created from 5 to 100 km of coral reefs using GIS functions, which may not reflect true distances in the real world. Our population estimates do not take into account accessibility of coral reefs to human settlements (J. E. Cinner et al., 2018).

Data Availability

Data and code for analysis are publicly accessible at https://github.com/amysw13/human_populations_by_coral_reefs

Conflicts of Interest

We declare that there are no conflicts of interest.

Acknowledgements

The authors would like to thank UNEP-WCMC for early discussions and feedback on this study. We also thank the reviewers for their comments during the peer review, which greatly improved the manuscript.

Author Contributions

MLT and ASW contributed to the study design; ASW curated the data and performed the analysis. SV contributed to analysis design. ASW wrote the original draft and, MLT and ASW reviewed and edited subsequent drafts.

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Supplementary Information

Methods and Materials

Coral Reef Countries

Total number of cells from LandScan 2018 raster used to calculate total population extractions for each coral reef country are present in Table S8.

São Tomé and Príncipe, and El Salvador were not analysed further for population analysis as their coral reefs were not in the coral reef distribution map and distance buffers did not overlap with those countries.

USA population statistics were taken just from the states that have coral reefs – Hawaii, Florida, and 100 km California and Arizona – the total country population was calculated using the total population of the states rather than the entire USA.

Vanuatu showed population extractions higher than the total country population and was re-extracted using polygon data frame just for Vanuatu. New Caledonia was also re-extracted to ensure that there was no overlap during global country-level extractions. On a regional level the USA encompasses the Pacific and Atlantic due to states bordering both the Atlantic and Pacific.

These countries were included in global and regional analysis and removed from finer scaled analysis:

- Pakistan, was removed from population analysis; this was due to only having population counts for 2000 and 2001 during population extraction.
- Paracel Islands and Spratly Islands, population counts only for 2016 and 2017.

There is variability in the number of coral reef countries included in the analysis due to variation across the LandScan data versions, for example Pakistan population extractions were only available for 2000 and 2001, however, due to the small population sizes these figures would not affect the overall trends reported.

Table S8. Summary of total number of cells from LandScan 2018 raster within distance buffers for each coral country.

ISO3	**Country**	**Distance Buffer**				
		5 km	**10 km**	**30 km**	**50 km**	**100 km**
ABW	Aruba	215	215	215	215	215
AIA	Anguilla	98	98	98	98	98
ARE	United Arab Emirates	1147	2897	13999	27903	60613
ASM	American Samoa	272	272	272	272	272
ATF	French Southern Territories	56	56	56	56	56
ATG	Antigua and Barbuda	472	533	534	534	534
AUS	Australia	19875	46133	176804	333241	776499
BES	Bonaire, Sint Eustatius and Saba	372	385	390	390	390
BHR	Bahrain	856	925	925	925	925
BHS	Bahamas	7761	12035	17136	17151	17151
BLM	Saint Barthélemy	29	29	29	29	29
BLZ	Belize	840	1694	8561	16251	26825
BMU	Bermuda	96	96	96	96	96
BRA	Brazil	4253	10432	41384	77379	183978
BRB	Barbados	414	527	527	527	527
CCK	Cocos Islands	20	20	20	20	20
CHN	China	2372	5491	23208	50535	126091
COK	Cook Islands	320	320	320	320	320
COL	Colombia	1396	4100	22012	46946	117676
COM	Comoros	1546	1994	2002	2002	2002
CRI	Costa Rica	1803	4576	19264	34464	54847
CUB	Cuba	11454	23943	74084	132555	139085
CUW	Curacao	527	528	529	529	529
CXR	Christmas Island	163	167	167	167	167
CYM	Cayman Islands	345	345	345	345	345
DJI	Djibouti	1656	3468	11140	18033	26099
DMA	Dominica	578	915	915	915	915
DOM	Dominican Republic	5140	10679	30753	45538	59377

ECU	Ecuador	1322	2769	7940	9120	9348
EGY	Egypt	10228	19956	57662	95092	186224
ERI	Eritrea	4678	8911	24332	41880	75726
FJI	Fiji	8664	12691	21785	23249	23249
FSM	Micronesia	891	917	917	917	917
GLP	Guadeloupe	1066	1507	2004	2004	2004
GRD	Grenada	386	432	432	432	432
GTM	Guatemala	41	149	2269	6326	27468
GUM	Guam	622	671	671	671	671
HKG	Hong Kong	10	94	799	1309	1426
HND	Honduras	470	1108	7679	16821	48559
HTI	Haiti	6296	12563	26118	30792	33453
IDN	Indonesia	136108	248454	590083	806018	1208992
IND	India	10077	20969	70769	133732	327934
IOT	British Indian Ocean Territory	80	80	80	80	80
IRN	Iran	1841	4845	22968	52463	154174
ISR	Israel	32	122	592	1286	4305
JAM	Jamaica	2961	5875	13038	13530	13530
JOR	Jordan	181	408	1782	4003	13134
JPN	Japan	4420	5456	6139	6673	11481
KEN	Kenya	2242	4827	15888	27096	55112
KHM	Cambodia	362	899	5085	12061	36111
KIR	Kiribati	1177	1196	1196	1196	1196
KNA	Saint Kitts and Nevis	327	327	327	327	327
KWT	Kuwait	156	515	4506	11041	22365
LCA	Saint Lucia	463	744	748	748	748
LKA	Sri Lanka	1479	3773	18133	34979	74637
MAF	Saint-Martin	63	69	69	69	69
MDG	Madagascar	12469	26565	97674	176367	375457
MDV	Maldives	342	343	343	343	343
MEX	Mexico	9869	28726	155039	325609	726677
MHL	Marshall Islands	362	362	362	362	362

MMR	Myanmar	4790	8331	27413	57120	133791
MNP	Northern Mariana Islands	385	385	396	412	488
MOZ	Mozambique	5260	11494	42315	78675	172915
MSR	Montserrat	126	126	126	126	126
MTQ	Martinique	609	934	1344	1344	1344
MUS	Mauritius	1445	2047	2520	2520	2520
MYS	Malaysia	5556	11122	41169	82648	189060
MYT	Mayotte	463	467	467	467	467
NCL	New Caledonia	7387	12713	23589	23589	23589
NIC	Nicaragua	64	226	2845	10720	44010
NIU	Niue	299	333	333	333	333
NRU	Nauru	25	25	25	25	25
OMN	Oman	3057	7054	30081	59035	139563
PAN	Panama	4028	7953	29900	58758	87968
PCN	Pitcairn Islands	73	73	73	73	73
PHL	Philippines	68275	120275	258326	307340	353864
PLW	Palau	521	565	565	565	565
PNG	Papua New Guinea	29610	50239	116104	164193	250461
PRI	Puerto Rico	2464	4857	11022	11022	11022
PYF	French Polynesia	3307	3669	3771	3771	3771
QAT	Qatar	852	1904	8785	12910	15012
REU	Reunion	328	749	2466	3145	3145
SAU	Saudi Arabia	13028	26391	83102	143830	303062
SDN	Sudan	2414	6259	22973	41014	86251
SGP	Singapore	107	293	815	815	815
SLB	Solomon Islands	19140	27924	33507	33828	33828
SOM	Somalia	2292	4984	18592	34766	87325
SXM	Sint Maarten	47	47	47	47	47
SYC	Seychelles	579	579	579	579	580
TCA	Turks and Caicos Islands	687	1136	1239	1239	1239
THA	Thailand	2194	4765	25253	50860	115869
TKL	Tokelau	17	17	17	17	17

TLS	Timor-Leste	2214	4891	14365	17458	17651
TON	Tonga	885	887	887	887	887
TTO	Trinidad and Tobago	487	642	1633	3356	5972
TUV	Tuvalu	43	43	43	43	43
TWN	Taiwan	2103	4072	12517	22793	45211
TZA	Tanzania	6764	12511	31541	50468	98934
UMI	United States Minor Outlying Islands	52	52	52	52	52
USA	United States	4494	9161	24373	39273	70608
VCT	Saint Vincent and the Grenadines	101	188	477	477	477
VEN	Venezuela	1869	3953	18027	34295	97554
VGB	British Virgin Islands	207	207	207	207	207
VIR	Virgin Islands, U.S.	439	442	442	442	442
VNM	Vietnam	3320	7405	31735	66721	181195
VUT	Vanuatu	9327	13168	14969	14980	14980
WLF	Wallis and Futuna	186	186	186	186	186
WSM	Samoa	1987	2999	3434	3434	3434
XCL	Clipperton Island	11	11	11	11	11
XPI	Paracel Islands	25	25	25	25	25
XSP	Spratly Islands	2	2	2	2	2
YEM	Yemen	3119	6590	24534	46714	110865
ZAF	South Africa	112	288	1394	3145	10128
BRN	Brunei	4	103	1748	3828	6783
BGD	Bangladesh	NA	NA	113	301	2348
ETH	Ethiopia	NA	NA	NA	218	23649
IRQ	Iraq	NA	NA	NA	11	4568
LAO	Laos	NA	NA	NA	NA	11430
MAC	Macao	NA	NA	NA	NA	45
PAK	Pakistan	NA	NA	NA	NA	1
SWZ	Swaziland	NA	NA	NA	NA	3081

Results

Population statistics

Proportion of country population by coral reefs (%) were calculated from the total population extracted from LandScan datasets and the distance buffers (1 km, 5 km, 10 km, 30 km, 50 km and 100 km) and total country population. Population growth of coral reef countries were obtained from The World Bank repository(The World Bank, 2018); these reflect the whole country (e.g. USA, for Hawaii). Yearly percentage population change and average population growth. Percentage change was compared to country population growth. LandScan does not recommend using their datasets for change detection particularly on a cell-by-cell comparison (Bhaduri et al., 2002), however our study aggregates population data to broad country scales which buffers against changes in Landscan over that time and Landscan has been found to be accurate when compared to other geographical estimates of population(Hall et al., 2012). Calculated area of distance categories within each country was calculated, in addition to entire country area in km^2.

Table S9. Summary of all coral reef countries, including ISO3 and ISO2 codes, Governing countries with ISO3 and ISO2 code, ocean regions adapted from (Burke et al., 2011a), region and income group taken from (The World Bank, 2018).

Country Name	**Sub Location**	**ISO3**	**ISO2**	**Governing Country**	**Governing ISO3**	**Governing ISO2**	**Ocean Region**	**Region**	**Income Group**
Aruba	Aruba	ABW	AW	Aruba	ABW	AW	Caribbean	Latin America & Caribbean	High income
Anguilla	Anguilla	AIA	AI	United Kingdom	GBR	GB	Caribbean	Latin America & Caribbean	Others
United Arab Emirates	United Arab Emirates	ARE	AE	United Arab Emirates	ARE	AE	Middle East	Middle East & North Africa	High income
American Samoa	American Samoa	ASM	AS	United States	USA	US	Pacific	East Asia & Pacific	Upper middle income
Bassas Da India	Bassas Da India	ATF	TF	France	FRA	FR	Indian Ocean	Indian Ocean	Others
Europa Island	Europa Island	ATF	TF	France	FRA	FR	Indian Ocean	Indian Ocean	Others
Glorioso Islands	Glorioso Islands	ATF	TF	France	FRA	FR	Indian Ocean	Indian Ocean	Others
Juan de Nova Island	Juan de Nova Island	ATF	TF	France	FRA	FR	Indian Ocean	Indian Ocean	Others

Country Name	Sub Location	ISO3	ISO2	Governing Country	Governing ISO3	Governing ISO2	Ocean Region	Region	Income Group
Tromelin Island	Tromelin Island	ATF	TF	France	FRA	FR	Indian Ocean	Indian Ocean	Others
Antigua and Barbuda	Antigua and Barbuda	ATG	AG	Antigua and Barbuda	ATG	AG	Caribbean	Latin America & Caribbean	High income
Australia	Ashmore and Cartier Islands	AUS	AU	Australia	AUS	AU	Australia	Indian Ocean	NA
Australia	Australia	AUS	AU	Australia	AUS	AU	Australia	East Asia & Pacific	High income
Bonaire	Bonaire	BES	BQ	Netherlands	NLD	NL	Caribbean	Latin America & Caribbean	Others
Saba	Saba	BES	BQ	Netherlands	NLD	NL	Caribbean	Latin America & Caribbean	Others
Sint Eustasius	Sint Eustasius	BES	BQ	Netherlands	NLD	NL	Caribbean	Latin America & Caribbean	Others

Country Name	Sub Location	ISO3	ISO2	Governing Country	Governing ISO3	Governing ISO2	Ocean Region	Region	Income Group
Bangladesh	Bangladesh	BGD	BD	Bangladesh	BGD	BD	Indian Ocean	South Asia	Lower middle income
Bahrain	Bahrain	BHR	BH	Bahrain	BHR	BH	Middle East	Middle East & North Africa	High income
The Bahamas	The Bahamas	BHS	BS	The Bahamas	BHS	BS	Caribbean	Latin America & Caribbean	High income
Saint Barthélemy	Saint Barthélemy	BLM	BL	France	FRA	FR	Caribbean	Latin America & Caribbean	High income
Belize	Belize	BLZ	BZ	Belize	BLZ	BZ	Caribbean	Latin America & Caribbean	Upper middle income
Bermuda	Bermuda	BMU	BM	United Kingdom	GBR	GB	Atlantic	North America	High income
Brazil	Brazil	BRA	BR	Brazil	BRA	BR	Atlantic	Latin America & Caribbean	Upper middle income

Country Name	Sub Location	ISO3	ISO2	Governing Country	Governing ISO3	Governing ISO2	Ocean Region	Region	Income Group
Barbados	Barbados	BRB	BB	Barbados	BRB	BB	Caribbean	Latin America & Caribbean	High income
Brunei Darussalam	Brunei Darussalam	BRN	BN	Brunei Darussalam	BRN	BN	Southeast Asia	East Asia & Pacific	High income
Cocos (Keeling) Islands	Cocos (Keeling) Islands	CCK	CC	Australia	AUS	AU	Australia	Indian Ocean	Others
China	China	CHN	CN	China	CHN	CN	Southeast Asia	East Asia & Pacific	Upper middle income
Cook Islands	Cook Islands	COK	CK	Cook Islands	COK	CK	Pacific	South Pacific Ocean	Others
Colombia	Colombia	COL	CO	Colombia	COL	CO	Caribbean	Latin America & Caribbean	Upper middle income
Comoros	Comoros	COM	KM	Comoros	COM	KM	Indian Ocean	Sub Saharan Africa	Low income
Cabo Verde	Cabo Verde	CPV	CV	Cabo Verde	CPV	CV	Indian Ocean	Sub Saharan Africa	Lower middle income

Country Name	Sub Location	ISO3	ISO2	Governing Country	Governing ISO3	Governing ISO2	Ocean Region	Region	Income Group
Costa Rica	Costa Rica	CRI	CR	Costa Rica	CRI	CR	Caribbean	Latin America & Caribbean	Upper middle income
Cuba	Cuba	CUB	CU	Cuba	CUB	CU	Caribbean	Latin America & Caribbean	Upper middle income
Curacao	Curacao	CUW	CW	Curacao	CUW	CW	Caribbean	Latin America & Caribbean	High income
Christmas Island	Christmas Island	CXR	CX	Australia	AUS	AU	Australia	Indian Ocean	Others
Cayman Islands	Cayman Islands	CYM	KY	United Kingdom	GBR	GB	Caribbean	Latin America & Caribbean	High income
Djibouti	Djibouti	DJI	DJ	Djibouti	DJI	DJ	Middle East	Middle East & North Africa	Lower middle income
Dominica	Dominica	DMA	DM	Dominica	DMA	DM	Caribbean	Latin America & Caribbean	Upper middle income

Country Name	Sub Location	ISO3	ISO2	Governing Country	Governing ISO3	Governing ISO2	Ocean Region	Region	Income Group
Dominican Republic	Dominican Republic	DOM	DO	Dominican Republic	DOM	DO	Caribbean	Latin America & Caribbean	Upper middle income
Ecuador	Ecuador	ECU	EC	Ecuador	ECU	EC	Caribbean	Latin America & Caribbean	Upper middle income
Egypt	Egypt	EGY	EG	Egypt	EGY	EG	Middle East	Middle East & North Africa	Lower middle income
Eritrea	Eritrea	ERI	ER	Eritrea	ERI	ER	Middle East	Sub_Saharan Africa	Low income
Ethiopia*	Ethiopia	ETH	ET	Ethiopia	ETH	ET	Middle East	Middle East & North Africa	Low income
Fiji	Fiji	FJI	FJ	Fiji	FJI	FJ	Pacific	East Asia & Pacific	Upper middle income
Micronesia	Micronesia	FSM	FM	Micronesia	FSM	FM	Pacific	East Asia & Pacific	Lower middle income
Guadeloupe	Guadeloupe	GLP	GP	Guadeloupe	GLP	GP	Caribbean	Latin America & Caribbean	Others

Country Name	Sub Location	ISO3	ISO2	Governing Country	Governing ISO3	Governing ISO2	Ocean Region	Region	Income Group
Grenada	Grenada	GRD	GD	Grenada	GRD	GD	Caribbean	Latin America & Caribbean	Upper middle income
Guatemala	Guatemala	GTM	GT	Guatemala	GTM	GT	Caribbean	Latin America & Caribbean	Upper middle income
Guam	Guam	GUM	GU	Guam	GUM	GU	Pacific	East Asia & Pacific	High income
Hong Kong	Hong Kong	HKG	HK	China	CHN	CN	Southeast Asia	East Asia & Pacific	High income
Honduras	Honduras	HND	HN	Honduras	HND	HN	Caribbean	Latin America & Caribbean	Lower middle income
Haiti	Haiti	HTI	HT	Haiti	HTI	HT	Caribbean	Latin America & Caribbean	Low income
Indonesia	Indonesia	IDN	ID	Indonesia	IDN	ID	Southeast Asia	East Asia & Pacific	Lower middle income
India	India	IND	IN	India	IND	IN	Indian Ocean	South Asia	Lower middle income

Country Name	Sub Location	ISO3	ISO2	Governing Country	Governing ISO3	Governing ISO2	Ocean Region	Region	Income Group
Chagos	Chagos	IOT	IO	United Kingdom	GBR	GB	Indian Ocean	Central Indian Ocean	Others
Iran	Iran	IRN	IR	Iran	IRN	IR	Middle East	Middle East & North Africa	Upper middle income
Iraq*	Iraq	IRQ	IQ	Iraq	IRQ	IQ	Middle East	Middle East & North Africa	Upper middle income
Israel	Israel	ISR	IL	Israel	ISR	IL	Middle East	Middle East & North Africa	High income
Jamaica	Jamaica	JAM	JM	Jamaica	JAM	JM	Caribbean	Latin America & Caribbean	Upper middle income
Jordan	Jordan	JOR	JO	Jordan	JOR	JO	Middle East	Middle East & North Africa	Upper middle income
Japan	Japan	JPN	JP	Japan	JPN	JP	Southeast Asia	East Asia & Pacific	High income
Kenya	Kenya	KEN	KE	Kenya	KEN	KE	Indian Ocean	Sub_Saharan Africa	Lower middle income

Country Name	Sub Location	ISO3	ISO2	Governing Country	Governing ISO3	Governing ISO2	Ocean Region	Region	Income Group
Cambodia	Cambodia	KHM	KH	Cambodia	KHM	KH	Southeast Asia	East Asia & Pacific	Lower middle income
Kiribati	Kiribati	KIR	KI	Kiribati	KIR	KI	Pacific	East Asia & Pacific	Lower middle income
Saint Kitts and Nevis	Saint Kitts and Nevis	KNA	KN	Saint Kitts and Nevis	KNA	KN	Caribbean	Latin America & Caribbean	High income
South Korea	South Korea	KOR	KR	South Korea	KOR	KR	Southeast Asia	East Asia & Pacific	High income
Kuwait	Kuwait	KWT	KW	Kuwait	KWT	KW	Middle East	Middle East & North Africa	High income
Loas*	Loas	LAO	LA	Loas	LAO	LA	Southeast Asia	East Asia & Pacific	Lower middle income
Saint Lucia	Saint Lucia	LCA	LC	Saint Lucia	LCA	LC	Caribbean	Latin America & Caribbean	Upper middle income
Sri Lanka	Sri Lanka	LKA	LK	Sri Lanka	LKA	LK	Indian Ocean	South Asia	Lower middle income
Macau	Macau	MAC	MO	Macau	CHN	CN	Southeast Asia	East Asia & Pacific	High income

Country Name	Sub Location	ISO3	ISO2	Governing Country	Governing ISO3	Governing ISO2	Ocean Region	Region	Income Group
Saint Martin	Saint Martin	MAF	MF	France	FRA	FR	Caribbean	Latin America & Caribbean	High income
Madagascar	Madagascar	MDG	MG	Madagascar	MDG	MG	Indian Ocean	Sub_Saharan Africa	Low income
Maldives	Maldives	MDV	MV	Maldives	MDV	MV	Indian Ocean	South Asia	Upper middle income
Mexico	Mexico	MEX	MX	Mexico	MEX	MX	Caribbean	Latin America & Caribbean	Upper middle income
Marshall Islands	Marshall Islands	MHL	MH	Marshall Islands	MHL	MH	Pacific	East Asia & Pacific	Upper middle income
Myanmar	Myanmar	MMR	MM	Myanmar	MMR	MM	Southeast Asia	East Asia & Pacific	Lower middle income
Northern Mariana Islands	Northern Mariana Islands	MNP	MP	United States	USA	US	Pacific	East Asia & Pacific	High income
Mozambique	Mozambique	MOZ	MZ	Mozambique	MOZ	MZ	Indian Ocean	Sub_Saharan Africa	Low income

Country Name	Sub Location	ISO3	ISO2	Governing Country	Governing ISO3	Governing ISO2	Ocean Region	Region	Income Group
Montserrat	Montserrat	MSR	MS	United Kingdom	GBR	GB	Caribbean	Latin America & Caribbean	Others
Martinique	Martinique	MTQ	MQ	France	FRA	FR	Caribbean	Latin America & Caribbean	Others
Mauritius	Mauritius	MUS	MU	Mauritius	MUS	MU	Indian Ocean	Sub_Saharan Africa	Upper middle income
Malaysia	Malaysia	MYS	MY	Malaysia	MYS	MY	Southeast Asia	East Asia & Pacific	Upper middle income
Mayotte	Mayotte	MYT	YT	France	FRA	FR	Indian Ocean	Sub_Saharan Africa	Others
New Caledonia	New Caledonia	NCL	NC	France	FRA	FR	Pacific	East Asia & Pacific	High income
Nicaragua	Nicaragua	NIC	NI	Nicaragua	NIC	NI	Caribbean	Latin America & Caribbean	Lower middle income
Niue	Niue	NIU	NU	Niue	NIU	NU	Pacific	East Asia & Pacific	Others
Nauru	Nauru	NRU	NR	Nauru	NRU	NR	Pacific	East Asia & Pacific	Upper middle income

Country Name	Sub Location	ISO3	ISO2	Governing Country	Governing ISO3	Governing ISO2	Ocean Region	Region	Income Group
Oman	Oman	OMN	OM	Oman	OMN	OM	Middle East	Middle East & North Africa	High income
Pakistan	Pakistan	PAK	PK	Pakistan	PAK	PK	Indian Ocean	South Asia	Lower middle income
Panama	Panama	PAN	PA	Panama	PAN	PA	Caribbean	Latin America & Caribbean	High income
Pitcairn Islands	Pitcairn Islands	PCN	PN	United Kingdom	GBR	GB	Pacific	East Asia & Pacific	Others
Philippines	Philippines	PHL	PH	Philippines	PHL	PH	Southeast Asia	East Asia & Pacific	Lower middle income
Palau	Palau	PLW	PW	Palau	PLW	PW	Southeast Asia	East Asia & Pacific	High income
Papua New Guinea	Papua New Guinea	PNG	PG	Papua New Guinea	PNG	PG	Pacific	East Asia & Pacific	Lower middle income
Puerto Rico	Puerto Rico	PRI	PR	United States	USA	US	Caribbean	Latin America & Caribbean	High income
French Polynesia	French Polynesia	PYF	PF	France	FRA	FR	Pacific	East Asia & Pacific	High income

Country Name	Sub Location	ISO3	ISO2	Governing Country	Governing ISO3	Governing ISO2	Ocean Region	Region	Income Group
Qatar	Qatar	QAT	QA	Qatar	QAT	QA	Middle East	Middle East & North Africa	High income
Réunion	Réunion	REU	RE	France	FRA	FR	Indian Ocean	Sub_Saharan Africa	Others
Saudi Arabia	Saudi Arabia	SAU	SA	Saudi Arabia	SAU	SA	Middle East	Middle East & North Africa	High income
Sudan	Sudan	SDN	SD	Sudan	SDN	SD	Middle East	Sub_Saharan Africa	Lower middle income
Singapore	Singapore	SGP	SG	Singapore	SGP	SG	Southeast Asia	East Asia & Pacific	High income
Solomon Islands	Solomon Islands	SLB	SB	Solomon Islands	SLB	SB	Pacific	East Asia & Pacific	Lower middle income
El Salvador	El Salvador	SLV	SV	El Salvador	SLV	SV	Pacific	Latin America & Caribbean	Lower middle income
Somalia	Somalia	SOM	SO	Somalia	SOM	SO	Indian Ocean	Sub_Saharan Africa	Low income
São Tomé and Príncipe	São Tomé and Príncipe	STP	ST	São Tomé and Príncipe	STP	ST	Atlantic	Sub_Saharan Africa	Lower middle income

Country Name	Sub Location	ISO3	ISO2	Governing Country	Governing ISO3	Governing ISO2	Ocean Region	Region	Income Group
Swaziland*	Swaziland	SWZ	SZ	Swaziland	SWZ	SZ	Indian Ocean	Sub_Saharan Africa	Lower middle income
Sint Maarten	Sint Maarten	SXM	SX	Sint Maarten	SXM	SX	Caribbean	Latin America & Caribbean	High income
Seychelles	Seychelles	SYC	SC	Seychelles	SYC	SC	Indian Ocean	Sub_Saharan Africa	High income
Turks and Caicos	Turks and Caicos	TCA	TC	United Kingdom	GBR	GB	Caribbean	Latin America & Caribbean	High income
Thailand	Thailand	THA	TH	Thailand	THA	TH	Southeast Asia	East Asia & Pacific	Upper middle income
Tokelau	Tokelau	TKL	TK	New Zealand	NZL	NZ	Pacific	East Asia & Pacific	Others
Timor-Leste	Timor-Leste	TLS	TL	Timor-Leste	TLS	TL	Southeast Asia	East Asia & Pacific	Lower middle income
Tonga	Tonga	TON	TO	Tonga	TON	TO	Pacific	East Asia & Pacific	Upper middle income

Country Name	**Sub Location**	**ISO3**	**ISO2**	**Governing Country**	**Governing ISO3**	**Governing ISO2**	**Ocean Region**	**Region**	**Income Group**
Trinidad and Tobago	Trinidad and Tobago	TTO	TT	Trinidad and Tobago	TTO	TT	Caribbean	Latin America & Caribbean	High income
Tuvalu	Tuvalu	TUV	TV	Tuvalu	TUV	TV	Pacific	East Asia & Pacific	Upper middle income
Taiwan	Taiwan	TWN	TW	Taiwan	TWN	TW	Southeast Asia	East Asia & Pacific	Upper middle income
Tanzania	Tanzania	TZA	TZ	Tanzania	TZA	TZ	Indian Ocean	Sub_Saharan Africa	Low income
Baker Island	Baker Island	UMI	UM	United States	USA	US	Pacific	East Asia & Pacific	Others
Howland Island	Howland Island	UMI	UM	United States	USA	US	Pacific	East Asia & Pacific	Others
Jarvis Island	Jarvis Island	UMI	UM	United States	USA	US	Pacific	East Asia & Pacific	Others
Johnston Atoll	Johnston Atoll	UMI	UM	United States	USA	US	Pacific	East Asia & Pacific	Others
Kingman Reef	Kingman Reef	UMI	UM	United States	USA	US	Pacific	East Asia & Pacific	Others
Midway Islands	Midway Islands	UMI	UM	United States	USA	US	Pacific	East Asia & Pacific	Others
Navassa Island	Navassa Island	UMI	UM	United States	USA	US	Pacific	East Asia & Pacific	Others

Country Name	Sub Location	ISO3	ISO2	Governing Country	Governing ISO3	Governing ISO2	Ocean Region	Region	Income Group
Palmyra Atoll	Palmyra Atoll	UMI	UM	United States	USA	US	Pacific	East Asia & Pacific	Others
Wake Island	Wake Island	UMI	UM	United States	USA	US	Pacific	East Asia & Pacific	Others
United States	Arizona	USA	US	United States	USA	US	Pacific	North America	High income
United States	California	USA	US	United States	USA	US	Pacific	North America	High income
United States	Florida	USA	US	United States	USA	US	Atlantic	North America	High income
United States	Hawaii	USA	US	United States	USA	US	Pacific	North America	High income
Saint Vincent and the Grenadines	Saint Vincent and the Grenadines	VCT	VC	Saint Vincent and the Grenadines	VCT	VC	Caribbean	Latin America & Caribbean	Upper middle income
Venezuela	Venezuela	VEN	VE	Venezuela	VEN	VE	Caribbean	Latin America & Caribbean	Upper middle income
British Virgin Islands	British Virgin Islands	VGB	VG	United Kingdom	GBR	GB	Caribbean	Latin America & Caribbean	High income

Country Name	Sub Location	ISO3	ISO2	Governing Country	Governing ISO3	Governing ISO2	Ocean Region	Region	Income Group
US Virgin Islands	US Virgin Islands	VIR	VI	United States	USA	US	Caribbean	Latin America & Caribbean	High income
Vietnam	Vietnam	VNM	VN	Vietnam	VNM	VN	Southeast Asia	East Asia & Pacific	Lower middle income
Vanuatu	Vanuatu	VUT	VU	Vanuatu	VUT	VU	Pacific	East Asia & Pacific	Lower middle income
Wallis and Futuna	Wallis and Futuna	WLF	WF	France	FRA	FR	Pacific	East Asia & Pacific	Others
Samoa	Samoa	WSM	WS	Samoa	WSM	WS	Pacific	East Asia & Pacific	Upper middle income
France	Clipperton Island	XCL	CP	France	FRA	FR	Pacific	North Pacific Ocean	Others
Paracel Islands	Paracel Islands	XPI					Southeast Asia	East Asia & Pacific	NA
Spratly Islands	Spratly Islands	XSP					Southeast Asia	East Asia & Pacific	NA
Yemen	Yemen	YEM	YE	Yemen	YEM	YE	Middle East	Middle East & North Africa	Low income

Country Name	Sub Location	ISO3	ISO2	Governing Country	Governing ISO3	Governing ISO2	Ocean Region	Region	Income Group
South Africa	South Africa	ZAF	ZA	South Africa	ZAF	ZA	Indian Ocean	Sub_Saharan Africa	Upper middle income

*Countries that are land locked and included in populations extractions at 100km from coral reefs.

Table S10. Summary of small island developing state coral reef countries, including ISO3 ocean regions adapted from (Burke et al., 2011a), region and income group taken from (The World Bank, 2018).

Country Name	ISO3	Ocean Region	Region	Income Group
Aruba	ABW	Caribbean	Latin America & Caribbean	High income
Anguilla	AIA	Caribbean	Latin America & Caribbean	Others
American Samoa	ASM	Pacific	East Asia & Pacific	Upper middle income
Antigua and Barbuda	ATG	Caribbean	Latin America & Caribbean	High income
Bahrain	BHR	Middle East	Middle East & North Africa	High income
The Bahamas	BHS	Caribbean	Latin America & Caribbean	High income
Belize	BLZ	Caribbean	Latin America & Caribbean	Upper middle income
Bermuda	BMU	Atlantic	North America	High income
Barbados	BRB	Caribbean	Latin America & Caribbean	High income
Cook Islands	COK	Pacific	South Pacific Ocean	Others
Comoros	COM	Indian Ocean	Sub Saharan Africa	Low income

Country Name	ISO3	Ocean Region	Region	Income Group
Cabo Verde	CPV	Indian Ocean	Sub Saharan Africa	Lower middle income
Cuba	CUB	Caribbean	Latin America & Caribbean	Upper middle income
Curacao	CUW	Caribbean	Latin America & Caribbean	High income
Cayman Islands	CYM	Caribbean	Latin America & Caribbean	High income
Dominica	DMA	Caribbean	Latin America & Caribbean	Upper middle income
Dominican Republic	DOM	Caribbean	Latin America & Caribbean	Upper middle income
Fiji	FJI	Pacific	East Asia & Pacific	Upper middle income
Micronesia	FSM	Pacific	East Asia & Pacific	Lower middle income
Guadeloupe	GLP	Caribbean	Latin America & Caribbean	Others
Grenada	GRD	Caribbean	Latin America & Caribbean	Upper middle income
Guam	GUM	Pacific	East Asia & Pacific	High income
Haiti	HTI	Caribbean	Latin America & Caribbean	Low income
Jamaica	JAM	Caribbean	Latin America & Caribbean	Upper middle income

Country Name	ISO3	Ocean Region	Region	Income Group
Kiribati	KIR	Pacific	East Asia & Pacific	Lower middle income
Saint Kitts and Nevis	KNA	Caribbean	Latin America & Caribbean	High income
Saint Lucia	LCA	Caribbean	Latin America & Caribbean	Upper middle income
Maldives	MDV	Indian Ocean	South Asia	Upper middle income
Marshall Islands	MHL	Pacific	East Asia & Pacific	Upper middle income
Northern Mariana Islands	MNP	Pacific	East Asia & Pacific	High income
Montserrat	MSR	Caribbean	Latin America & Caribbean	Others
Martinique	MTQ	Caribbean	Latin America & Caribbean	Others
Mauritius	MUS	Indian Ocean	Sub_Saharan Africa	Upper middle income
New Caledonia	NCL	Pacific	East Asia & Pacific	High income
Niue	NIU	Pacific	East Asia & Pacific	Others
Nauru	NRU	Pacific	East Asia & Pacific	Upper middle income
Palau	PLW	Southeast Asia	East Asia & Pacific	High income

Country Name	ISO3	Ocean Region	Region	Income Group
Papua New Guinea	PNG	Pacific	East Asia & Pacific	Lower middle income
Puerto Rico	PRI	Caribbean	Latin America & Caribbean	High income
French Polynesia	PYF	Pacific	East Asia & Pacific	High income
Singapore	SGP	Southeast Asia	East Asia & Pacific	High income
Solomon Islands	SLB	Pacific	East Asia & Pacific	Lower middle income
São Tomé and Príncipe	STP	Atlantic	Sub_Saharan Africa	Lower middle income
Sint Maarten	SXM	Caribbean	Latin America & Caribbean	High income
Seychelles	SYC	Indian Ocean	Sub_Saharan Africa	High income
Turks and Caicos	TCA	Caribbean	Latin America & Caribbean	High income
Timor-Leste	TLS	Southeast Asia	East Asia & Pacific	Lower middle income
Tonga	TON	Pacific	East Asia & Pacific	Upper middle income
Trinidad and Tobago	TTO	Caribbean	Latin America & Caribbean	High income
Tuvalu	TUV	Pacific	East Asia & Pacific	Upper middle income

Country Name	ISO3	Ocean Region	Region	Income Group
Saint Vincent and the Grenadines	VCT	Caribbean	Latin America & Caribbean	Upper middle income
British Virgin Islands	VGB	Caribbean	Latin America & Caribbean	High income
US Virgin Islands	VIR	Caribbean	Latin America & Caribbean	High income
Vanuatu	VUT	Pacific	East Asia & Pacific	Lower middle income
Samoa	WSM	Pacific	East Asia & Pacific	Upper middle income

Table S11. Number of coral reef countries included in analysis over years and across distance buffers of 5 km, 10 km, 30 km, 50 km, 100 km.

Year	**5 km**	**10 km**	**30 km**	**50 km**	**100 km**
2000	109	109	110	112	116
2001	108	108	109	111	115
2002	109	109	110	112	115
2003	109	109	110	112	115
2004	109	109	110	112	115
2005	109	109	110	112	115
2006	109	109	110	112	115
2007	108	108	109	111	114
2008	109	109	110	112	115
2009	109	109	110	112	115
2010	109	109	110	112	115
2011	109	109	110	112	115
2012	109	109	110	112	115
2013	109	109	110	112	115
2014	109	109	110	112	115
2015	109	109	110	112	115
2016	111	111	112	114	117
2017	111	111	112	114	117
2018	111	111	112	114	117
2019	111	111	112	114	117
2020	111	111	112	114	117

Table S12. Number of coral reef countries included in analysis over all years and across distance buffers of 5 km, 10 km, 30 km, 50 km, 100 km grouped by region.

Year	**Distance**	**Atlantic***	**Australia**	**Caribbean**	**Indian Ocean**	**Middle East**	**Pacific***	**Southeast Asia**	**Total***
2000	5 km	3	3	38	14	14	23	15	109
2000	10 km	3	3	38	14	14	23	15	109
2000	30 km	3	3	38	15	14	23	15	110
2000	50 km	3	3	38	15	16	23	15	112
2000	100 km	3	3	38	17	16	23	17	116
2001	5 km	3	3	38	14	14	22	15	108
2001	10 km	3	3	38	14	14	22	15	108
2001	30 km	3	3	38	15	14	22	15	109
2001	50 km	3	3	38	15	16	22	15	111
2001	100 km	3	3	38	17	16	22	17	115
2002	5 km	3	3	38	14	14	23	15	109
2002	10 km	3	3	38	14	14	23	15	109
2002	30 km	3	3	38	15	14	23	15	110
2002	50 km	3	3	38	15	16	23	15	112
2002	100 km	3	3	38	16	16	23	17	115
2003	5 km	3	3	38	14	14	23	15	109
2003	10 km	3	3	38	14	14	23	15	109
2003	30 km	3	3	38	15	14	23	15	110
2003	50 km	3	3	38	15	16	23	15	112
2003	100 km	3	3	38	16	16	23	17	115
2004	5 km	3	3	38	14	14	23	15	109
2004	10 km	3	3	38	14	14	23	15	109
2004	30 km	3	3	38	15	14	23	15	110
2004	50 km	3	3	38	15	16	23	15	112
2004	100 km	3	3	38	16	16	23	17	115
2005	5 km	3	3	38	14	14	23	15	109
2005	10 km	3	3	38	14	14	23	15	109
2005	30 km	3	3	38	15	14	23	15	110

Year	**Distance**	**Atlantic***	**Australia**	**Caribbean**	**Indian Ocean**	**Middle East**	**Pacific***	**Southeast Asia**	**Total***
2005	50 km	3	3	38	15	16	23	15	112
2005	100 km	3	3	38	16	16	23	17	115
2006	5 km	3	3	38	14	14	23	15	109
2006	10 km	3	3	38	14	14	23	15	109
2006	30 km	3	3	38	15	14	23	15	110
2006	50 km	3	3	38	15	16	23	15	112
2006	100 km	3	3	38	16	16	23	17	115
2007	5 km	3	3	38	14	14	22	15	108
2007	10 km	3	3	38	14	14	22	15	108
2007	30 km	3	3	38	15	14	22	15	109
2007	50 km	3	3	38	15	16	22	15	111
2007	100 km	3	3	38	16	16	22	17	114
2008	5 km	3	3	38	14	14	23	15	109
2008	10 km	3	3	38	14	14	23	15	109
2008	30 km	3	3	38	15	14	23	15	110
2008	50 km	3	3	38	15	16	23	15	112
2008	100 km	3	3	38	16	16	23	17	115
2009	5 km	3	3	38	14	14	23	15	109
2009	10 km	3	3	38	14	14	23	15	109
2009	30 km	3	3	38	15	14	23	15	110
2009	50 km	3	3	38	15	16	23	15	112
2009	100 km	3	3	38	16	16	23	17	115
2010	5 km	3	3	38	14	14	23	15	109
2010	10 km	3	3	38	14	14	23	15	109
2010	30 km	3	3	38	15	14	23	15	110
2010	50 km	3	3	38	15	16	23	15	112
2010	100 km	3	3	38	16	16	23	17	115
2011	5 km	3	3	38	14	14	23	15	109
2011	10 km	3	3	38	14	14	23	15	109
2011	30 km	3	3	38	15	14	23	15	110
2011	50 km	3	3	38	15	16	23	15	112

Year	Distance	Atlantic*	Australia	Caribbean	Indian Ocean	Middle East	Pacific*	Southeast Asia	Total*
2011	100 km	3	3	38	16	16	23	17	115
2012	5 km	3	3	38	14	14	23	15	109
2012	10 km	3	3	38	14	14	23	15	109
2012	30 km	3	3	38	15	14	23	15	110
2012	50 km	3	3	38	15	16	23	15	112
2012	100 km	3	3	38	16	16	23	17	115
2013	5 km	3	3	38	14	14	23	15	109
2013	10 km	3	3	38	14	14	23	15	109
2013	30 km	3	3	38	15	14	23	15	110
2013	50 km	3	3	38	15	16	23	15	112
2013	100 km	3	3	38	16	16	23	17	115
2014	5 km	3	3	38	14	14	23	15	109
2014	10 km	3	3	38	14	14	23	15	109
2014	30 km	3	3	38	15	14	23	15	110
2014	50 km	3	3	38	15	16	23	15	112
2014	100 km	3	3	38	16	16	23	17	115
2015	5 km	3	3	38	14	14	23	15	109
2015	10 km	3	3	38	14	14	23	15	109
2015	30 km	3	3	38	15	14	23	15	110
2015	50 km	3	3	38	15	16	23	15	112
2015	100 km	3	3	38	16	16	23	17	115
2016	5 km	3	3	38	14	14	23	17	111
2016	10 km	3	3	38	14	14	23	17	111
2016	30 km	3	3	38	15	14	23	17	112
2016	50 km	3	3	38	15	16	23	17	114
2016	100 km	3	3	38	16	16	23	19	117
2017	5 km	3	3	38	14	14	23	17	111
2017	10 km	3	3	38	14	14	23	17	111
2017	30 km	3	3	38	15	14	23	17	112

Year	Distance	Atlantic*	Australia	Caribbean	Indian Ocean	Middle East	Pacific*	Southeast Asia	Total*
2017	50 km	3	3	38	15	16	23	17	114
2017	100 km	3	3	38	16	16	23	19	117
2018	5 km	3	3	38	14	14	23	17	111
2018	10 km	3	3	38	14	14	23	17	111
2018	30 km	3	3	38	15	14	23	17	112
2018	50 km	3	3	38	15	16	23	17	114
2018	100 km	3	3	38	16	16	23	19	117
2019	5 km	3	3	38	14	14	23	17	111
2019	10 km	3	3	38	14	14	23	17	111
2019	30 km	3	3	38	15	14	23	17	112
2019	50 km	3	3	38	15	16	23	17	114
2019	100 km	3	3	38	16	16	23	19	117
2020	5 km	3	3	38	14	14	23	17	111
2020	10 km	3	3	38	14	14	23	17	111
2020	30 km	3	3	38	15	14	23	17	112
2020	50 km	3	3	38	15	16	23	17	114
2020	100 km	3	3	38	16	16	23	19	117

*United States has areas of coral reefs that are found in the Atlantic and Pacific ocean regions, therefore only counted once in the total.

Table S13. Number of coral reef countries included in analysis over years and across distance buffers of 5 km, 10 km, 30 km, 50 km, 100 km grouped by Income group.

Year	**Distance**	**Low**	**Lower middle**	**Upper middle**	**High**	**Total**
2000	5 km	8	19	31	36	94
2000	10 km	8	19	31	36	94
2000	30 km	8	20	31	36	95
2000	50 km	9	20	32	36	97
2000	100 km	9	23	32	37	101
2001	5 km	8	19	31	36	94
2001	10 km	8	19	31	36	94
2001	30 km	8	20	31	36	95
2001	50 km	9	20	32	36	97
2001	100 km	9	23	32	37	101
2002	5 km	8	19	31	36	94
2002	10 km	8	19	31	36	94
2002	30 km	8	20	31	36	95
2002	50 km	9	20	32	36	97
2002	100 km	9	22	32	37	100
2003	5 km	8	19	31	36	94
2003	10 km	8	19	31	36	94
2003	30 km	8	20	31	36	95
2003	50 km	9	20	32	36	97
2003	100 km	9	22	32	37	100
2004	5 km	8	19	31	36	94
2004	10 km	8	19	31	36	94
2004	30 km	8	20	31	36	95
2004	50 km	9	20	32	36	97
2004	100 km	9	22	32	37	100
2005	5 km	8	19	31	36	94
2005	10 km	8	19	31	36	94
2005	30 km	8	20	31	36	95

Year	**Distance**	**Low**	**Lower middle**	**Upper middle**	**High**	**Total**
2005	50 km	9	20	32	36	97
2005	100 km	9	22	32	37	100
2006	5 km	8	19	31	36	94
2006	10 km	8	19	31	36	94
2006	30 km	8	20	31	36	95
2006	50 km	9	20	32	36	97
2006	100 km	9	22	32	37	100
2007	5 km	8	19	31	36	94
2007	10 km	8	19	31	36	94
2007	30 km	8	20	31	36	95
2007	50 km	9	20	32	36	97
2007	100 km	9	22	32	37	100
2008	5 km	8	19	31	36	94
2008	10 km	8	19	31	36	94
2008	30 km	8	20	31	36	95
2008	50 km	9	20	32	36	97
2008	100 km	9	22	32	37	100
2009	5 km	8	19	31	36	94
2009	10 km	8	19	31	36	94
2009	30 km	8	20	31	36	95
2009	50 km	9	20	32	36	97
2009	100 km	9	22	32	37	100
2010	5 km	8	19	31	36	94
2010	10 km	8	19	31	36	94
2010	30 km	8	20	31	36	95
2010	50 km	9	20	32	36	97
2010	100 km	9	22	32	37	100
2011	5 km	8	19	31	36	94
2011	10 km	8	19	31	36	94
2011	30 km	8	20	31	36	95
2011	50 km	9	20	32	36	97

Year	Distance	Low	Lower middle	Upper middle	High	Total
2011	100 km	9	22	32	37	100
2012	5 km	8	19	31	36	94
2012	10 km	8	19	31	36	94
2012	30 km	8	20	31	36	95
2012	50 km	9	20	32	36	97
2012	100 km	9	22	32	37	100
2013	5 km	8	19	31	36	94
2013	10 km	8	19	31	36	94
2013	30 km	8	20	31	36	95
2013	50 km	9	20	32	36	97
2013	100 km	9	22	32	37	100
2014	5 km	8	19	31	36	94
2014	10 km	8	19	31	36	94
2014	30 km	8	20	31	36	95
2014	50 km	9	20	32	36	97
2014	100 km	9	22	32	37	100
2015	5 km	8	19	31	36	94
2015	10 km	8	19	31	36	94
2015	30 km	8	20	31	36	95
2015	50 km	9	20	32	36	97
2015	100 km	9	22	32	37	100
2016	5 km	8	19	31	36	94
2016	10 km	8	19	31	36	94
2016	30 km	8	20	31	36	95
2016	50 km	9	20	32	36	97
2016	100 km	9	22	32	37	100
2017	5 km	8	19	31	36	94
2017	10 km	8	19	31	36	94
2017	30 km	8	20	31	36	95
2017	50 km	9	20	32	36	97

Year	Distance	Low	Lower middle	Upper middle	High	Total
2017	100 km	9	22	32	37	100
2018	5 km	8	19	31	36	94
2018	10 km	8	19	31	36	94
2018	30 km	8	20	31	36	95
2018	50 km	9	20	32	36	97
2018	100 km	9	22	32	37	100
2019	5 km	8	19	31	36	94
2019	10 km	8	19	31	36	94
2019	30 km	8	20	31	36	95
2019	50 km	9	20	32	36	97
2019	100 km	9	22	32	37	100
2020	5 km	8	19	31	36	94
2020	10 km	8	19	31	36	94
2020	30 km	8	20	31	36	95
2020	50 km	9	20	32	36	97
2020	100 km	9	22	32	37	100

Table S14. Summary of coral reef area(km^2) and coral reef proportion (%) by country.

Rank	**Country Name**	**Sub Location**	**ISO3**	**Governing Country**	**Ocean Region**	**Coral Reef Area (km^2)**	**Coral reef Proportion (%)**
1	Australia	Australia	AUS	Australia	Australia	31688.43	20.93
2	Indonesia	Indonesia	IDN	Indonesia	Southeast Asia	20233.23	13.36
3	Philippines	Philippines	PHL	Philippines	Southeast Asia	13573.40	8.97
4	Papua New Guinea	Papua New Guinea	PNG	Papua New Guinea	Pacific	7260.16	4.80
5	New Caledonia	New Caledonia	NCL	France	Pacific	4574.82	3.02
6	United States	Arizona	USA	United States	Pacific	4091.48	2.70
7	Saudi Arabia	Saudi Arabia	SAU	Saudi Arabia	Middle East	3420.34	2.26
8	Fiji	Fiji	FJI	Fiji	Pacific	3380.61	2.23
9	Micronesia	Micronesia	FSM	Micronesia	Pacific	3171.84	2.10
10	Madagascar	Madagascar	MDG	Madagascar	Indian Ocean	3109.86	2.05
11	French Polynesia	French Polynesia	PYF	France	Pacific	2999.88	1.98
12	Solomon Islands	Solomon Islands	SLB	Solomon Islands	Pacific	2803.91	1.85
13	Maldives	Maldives	MDV	Maldives	Indian Ocean	2696.11	1.78
14	Cuba	Cuba	CUB	Cuba	Caribbean	2691.87	1.78
15	The Bahamas	The Bahamas	BHS	The Bahamas	Caribbean	2226.52	1.47
16	Egypt	Egypt	EGY	Egypt	Middle East	2207.27	1.46
17	Malaysia	Malaysia	MYS	Malaysia	Southeast Asia	2150.32	1.42

Rank	Country Name	Sub Location	ISO3	Governing Country	Ocean Region	Coral Reef Area (km^2)	Coral reef Proportion (%)
18	Tanzania	Tanzania	TZA	Tanzania	Indian Ocean	2104.20	1.39
19	Mozambique	Mozambique	MOZ	Mozambique	Indian Ocean	2072.50	1.37
20	India	India	IND	India	Indian Ocean	2036.47	1.35
21	Marshall Islands	Marshall Islands	MHL	Marshall Islands	Pacific	1992.45	1.32
22	Kiribati	Kiribati	KIR	Kiribati	Pacific	1960.04	1.29
23	NA	NA	IOT/ MUS	NA	Indian Ocean	1800.25	1.19
24	Eritrea	Eritrea	ERI	Eritrea	Middle East	1583.19	1.05
25	Seychelles	Seychelles	SYC	Seychelles	Indian Ocean	1512.60	1.00
26	China	China	CHN	China	Southeast Asia	1145.13	0.756
27	Japan	Japan	JPN	Japan	Southeast Asia	1038.87	0.686
28	Tonga	Tonga	TON	Tonga	Pacific	992.05	0.655
29	NA	NA	SDN/ EGY	NA	Middle East	965.81	0.638
30	Colombia	Colombia	COL	Colombia	Caribbean	935.05	0.618
31	Mexico	Mexico	MEX	Mexico	Caribbean	931.10	0.615
32	Tuvalu	Tuvalu	TUV	Tuvalu	Pacific	885.57	0.585
33	Belize	Belize	BLZ	Belize	Caribbean	873.90	0.577
34	Honduras	Honduras	HND	Honduras	Caribbean	833.28	0.550
35	Mauritius	Mauritius	MUS	Mauritius	Indian Ocean	753.77	0.498
36	Vanuatu	Vanuatu	VUT	Vanuatu	Pacific	706.93	0.467
37	Brazil	Brazil	BRA	Brazil	Atlantic	697.57	0.461

Rank	**Country Name**	**Sub Location**	**ISO3**	**Governing Country**	**Ocean Region**	**Coral Reef Area (km^2)**	**Coral reef Proportion (%)**
38	Sudan	Sudan	SDN	Sudan	Middle East	684.77	0.452
39	Yemen	Yemen	YEM	Yemen	Middle East	657.53	0.434
40	Panama	Panama	PAN	Panama	Caribbean	630.52	0.416
41	Myanmar	Myanmar	MMR	Myanmar	Southeast Asia	607.13	0.401
42	Bermuda	Bermuda	BMU	United Kingdom	Atlantic	528.92	0.349
43	Palau	Palau	PLW	Palau	Southeast Asia	506.40	0.334
44	Kenya	Kenya	KEN	Kenya	Indian Ocean	504.13	0.333
45	Vietnam	Vietnam	VNM	Vietnam	Southeast Asia	478.15	0.316
46	Nicaragua	Nicaragua	NIC	Nicaragua	Caribbean	460.83	0.304
47	Jamaica	Jamaica	JAM	Jamaica	Caribbean	412.68	0.273
48	Wallis and Futuna	Wallis and Futuna	WLF	France	Pacific	411.16	0.272
49	Somalia	Somalia	SOM	Somalia	Indian Ocean	411.04	0.272
50	Taiwan	Taiwan	TWN	Taiwan	Southeast Asia	375.16	0.248
51	Dominican Republic	Dominican Republic	DOM	Dominican Republic	Caribbean	350.60	0.232
52	Venezuela	Venezuela	VEN	Venezuela	Caribbean	346.65	0.229
53	Haiti	Haiti	HTI	Haiti	Caribbean	325.60	0.215
54	Oman	Oman	OMN	Oman	Middle East	276.80	0.183
55	Cook Islands	Cook Islands	COK	Cook Islands	Pacific	253.27	0.167

Rank	Country Name	Sub Location	ISO3	Governing Country	Ocean Region	Coral Reef Area (km^2)	Coral reef Proportion (%)
56	Djibouti	Djibouti	DJI	Djibouti	Middle East	247.19	0.163
57	NA	NA	MDG /FRA	NA	Indian Ocean	235.08	0.155
58	Comoros	Comoros	COM	Comoros	Indian Ocean	220.57	0.146
59	Bahrain	Bahrain	BHR	Bahrain	Middle East	207.80	0.137
60	Samoa	Samoa	WSM	Samoa	Pacific	200.00	0.132
61	Caribbean Antilles	Bonaire	BES	Netherlands	Caribbean	198.30	0.131
62	Turks and Caicos	Turks and Caicos	TCA	United Kingdom	Caribbean	191.63	0.127
63	Thailand	Thailand	THA	Thailand	Southeast Asia	184.19	0.122
64	Cayman Islands	Cayman Islands	CYM	United Kingdom	Caribbean	178.95	0.118
65	French Southern Territories	Bassas Da India	ATF	France	Indian Ocean	175.67	0.116
66	United States Minor Outlying Islands	Baker Island	UMI	United States	Pacific	171.45	0.113
67	Mayotte	Mayotte	MYT	France	Indian Ocean	166.23	0.110
68	Puerto Rico	Puerto Rico	PRI	United States	Caribbean	158.14	0.104
69	Qatar	Qatar	QAT	Qatar	Middle East	155.39	0.103
70	British Virgin Islands	British Virgin Islands	VGB	United Kingdom	Caribbean	137.13	0.091
71	Guam	Guam	GUM	United States	Pacific	136.87	0.090
72	NA	NA	MYT/ COM	NA	Indian Ocean	133.79	0.088

Rank	**Country Name**	**Sub Location**	**ISO3**	**Governing Country**	**Ocean Region**	**Coral Reef Area (km^2)**	**Coral reef Proportion (%)**
73	United Arab Emirates	United Arab Emirates	ARE	United Arab Emirates	Middle East	126.76	0.084
74	Ecuador	Ecuador	ECU	Ecuador	Caribbean	125.42	0.083
75	Iran	Iran	IRN	Iran	Middle East	117.79	0.078
76	Australia	Cocos (Keeling) Islands	CCK	Australia	Indian Ocean	115.15	0.076
77	Guadeloupe	Guadeloupe	GLP	France	Caribbean	113.33	0.075
78	Sri Lanka	Sri Lanka	LKA	Sri Lanka	Indian Ocean	108.90	0.072
79	Tokelau	Tokelau	TKL	New Zealand	Pacific	96.57	0.064
80	Northern Mariana Islands	Northern Mariana Islands	MNP	United States	Pacific	81.40	0.054
81	Kuwait	Kuwait	KWT	Kuwait	Middle East	72.75	0.048
82	Martinique	Martinique	MTQ	France	Caribbean	72.01	0.048
83	Costa Rica	Costa Rica	CRI	Costa Rica	Caribbean	69.86	0.046
84	Aruba	Aruba	ABW	Netherlands	Caribbean	66.53	0.044
85	Brunei Darussalam	Brunei Darussalam	BRN	Brunei Darussalam	Southeast Asia	62.74	0.041
86	Antigua and Barbuda	Antigua and Barbuda	ATG	Antigua and Barbuda	Caribbean	54.89	0.036
87	Cambodia	Cambodia	KHM	Cambodia	Southeast Asia	47.46	0.031
88	Curacao	Curacao	CUW	Netherlands	Caribbean	46.87	0.031

Rank	**Country Name**	**Sub Location**	**ISO3**	**Governing Country**	**Ocean Region**	**Coral Reef Area (km^2)**	**Coral reef Proportion (%)**
89	Grenada	Grenada	GRD	Grenada	Caribbean	45.78	0.030
90	American Samoa	American Samoa	ASM	United States	Pacific	45.16	0.030
91	Saint Kitts and Nevis	Saint Kitts and Nevis	KNA	Saint Kitts and Nevis	Caribbean	41.82	0.028
92	Pitcairn Islands	Pitcairn Islands	PCN	United Kingdom	Pacific	39.40	0.026
93	Saint Vincent and the Grenadines	Saint Vincent and the Grenadines	VCT	Saint Vincent and the Grenadines	Caribbean	38.37	0.025
94	NA	NA	PNG/ AUS	NA	Australia	36.46	0.024
95	Timor-Leste	Timor-Leste	TLS	Timor-Leste	Southeast Asia	35.06	0.023
96	US Virgin Islands	US Virgin Islands	VIR	United States	Caribbean	33.52	0.022
97	Trinidad and Tobago	Trinidad and Tobago	TTO	Trinidad and Tobago	Caribbean	32.03	0.021
98	Barbados	Barbados	BRB	Barbados	Caribbean	31.22	0.021
99	Saint Lucia	Saint Lucia	LCA	Saint Lucia	Caribbean	29.48	0.019
100	NA	NA	HTI/ USA/ JAM	NA	Caribbean	26.16	0.017
101	Anguilla	Anguilla	AIA	United Kingdom	Caribbean	24.33	0.016
102	Dominica	Dominica	DMA	Dominica	Caribbean	16.36	0.011
103	Niue	Niue	NIU	Niue	Pacific	15.38	0.010
104	Réunion	Réunion	REU	France	Indian Ocean	12.12	0.008
105	Saint Barthélemy	Saint Barthélemy	BLM	France	Caribbean	10.71	0.007

Rank	Country Name	Sub Location	ISO3	Governing Country	Ocean Region	Coral Reef Area (km^2)	Coral reef Proportion (%)
106	British Indian Ocean Territory	Chagos	IOT	United Kingdom	Indian Ocean	9.82	0.006
107	NA	NA	TWN/ JPN/ CHN	NA	Southeast Asia	6.60	0.004
108	NA	NA	EGY/ SDN	NA	Middle East	6.35	0.004
109	Saint Martin	Saint Martin	MAF	France	Caribbean	6.21	0.004
110	Nauru	Nauru	NRU	Nauru	Pacific	5.92	0.004
111	NA	NA	ATF/ MUS/ MDG	NA	Indian Ocean	5.41	0.004
112	Australia	Christmas Island	CXR	Australia	Indian Ocean	5.03	0.003
113	NA	NA	ABNJ	NA	High Seas	4.94	0.003
114	Bangladesh	Bangladesh	BGD	Bangladesh	Indian Ocean	4.53	0.003
115	NA	NA	CPT	NA	Pacific	4.30	0.003
116	Singapore	Singapore	SGP	Singapore	Southeast Asia	3.85	0.003
117	Jordan	Jordan	JOR	Jordan	Middle East	2.88	0.002
118	NA	NA	ATF/ MDG	NA	Indian Ocean	2.84	0.002
119	Montserrat	Montserrat	MSR	United Kingdom	Caribbean	2.42	0.002
120	Sint Maarten	Sint Maarten	SXM	Netherlands	Caribbean	1.70	0.001
121	South Africa	South Africa	ZAF	South Africa	Indian Ocean	1.40	0.001
122	Israel	Israel	ISR	Israel	Middle East	1.14	0.001

Rank	**Country Name**	**Sub Location**	**ISO3**	**Governing Country**	**Ocean Region**	**Coral Reef Area (km^2)**	**Coral reef Proportion (%)**
123	NA	NA	ARE/ IRN	NA	Middle East	1.12	0.001
124	NA	NA	KEN/ SOM	NA	Indian Ocean	0.96	0.001
125	NA	NA	CHN/ TWN/ JPN	NA	Southeast Asia	0.49	0.000
126	NA	NA	QAT/ SAU/ ARE	NA	Middle East	0.05	0.000
127	NA	NA	REU/ MUS	NA	Indian Ocean	0.00	0.000

Table S15. Summary statistics of global populations near coral reefs from 5 km to 100 km in 2000 and 2020.

Distance from Coral Reefs	**Population (millions)**		**Total Global Population (billions) †**		**Proportion of Population to Global Population (%)**		**Percentage change in Population (2000 - 2020)**	**Average Population Growth (%, 2000 - 2020)**	**World Population Growth (%)†**		**Area of Land (km^2)**		**Population Density (per km^2)**		**World Population Density (per km^2) †**	
	2000	**2020**	**2000**	**2020**	**2000**	**2020**			**2000**	**2020**	**2000**	**2020**	**2000**	**2020**	**2000**	**2020**
5 km	75.85	108	6.07	7.76	1.25	1.39	42.17	1.78	1.32	1.04	413,285	413,307	184	261	47	60
10 km	143.24	195.61			2.36	2.52	36.56	1.57			772,204	772,225	185	253		
30 km	335.38	433.88			5.53	5.59	29.37	1.30			2,098,951	2,098,972	160	207		
50 km	486.54	629.85			8.02	8.11	29.45	1.30			3,381,042	3,381,064	144	186		
100 km	762.06	996.51			12.56	12.84	30.77	1.35			6,381,056	6,381,077	119	156		

† Data from (The World Bank, 2018)

Table S16. Summary statistics of regional populations near coral reefs from 5 km to 100 km in 2000 and 2020.

Region	Distance from Coral Reefs	Population (millions)		Total Regional Population (millions)†		Proportion of Population to Total regional Population (%)		% increase in Population (2000 - 2020)	Average Population Growth (%, 2000 - 2020)	Area of Land (km^2)		Population Density (per km^2)	
		2000	2020	2000	2020	2000	2020			2000	2020	2000	2020
Atlantic	**5 km**	3.89	4.86	188.16	232.30	2.07	2.09	25.09	1.14	4405		883	1104
	10 km	7.96	10.49			4.23	4.52	31.81	1.40	10,635		748	986
	30 km	14.35	19.31			7.63	8.31	34.54	1.51	41,788		343	462
	50 km	16.13	22.11			8.57	9.52	37.11	1.62	77,925		207	284
	100 km	21.59	28.69			11.47	12.35	32.89	1.47	182,577		118	157
Australia	**5 km**	0.22	0.31	19.07	25.15	1.14	1.21	40.08	2.88	16,316		13	19
	10 km	0.49	0.76			2.54	3.01	55.82	2.50	37,621		13	20
	30 km	3.69	4.96			19.34	19.73	34.56	1.52	143,229		26	35
	50 km	5.42	7.99			28.40	31.79	47.63	1.98	269,115		20	30
	100 km	6.03	9.33			31.64	37.10	54.61	2.23	622,971		10	15
Caribbean	**5 km**	12.15	15.67	242.21	306.34	5.02	5.12	29.01	1.29	53,283		228	294
	10 km	22.09	28.21			9.12	9.21	27.70	1.24	109,643		201	257
	30 km	44.44	55.44			18.35	18.10	24.75	1.12	369,410		120	150
	50 km	64.27	77.65			26.53	25.35	20.82	0.96	654,811		98	119
	100 km	90.06	109.86			37.18	35.86	21.98	1.00	1,235,322		73	89
Indian Ocean	**5 km**	12.31	21.06	1,185.18	1,588.31	1.04	1.33	71.05	2.77	37,486		329	562
	10 km	29.08	42.61			2.45	2.68	46.52	1.95	75,809		384	562
	30 km	63.27	85.49	1,314.01	1,751.70	4.82	4.88	35.11	1.54	251,408		252	340
	50 km	91.58	122.89			6.97	7.02	34.19	1.50	451,608		203	272
	100 km	162.67	215.77	1,456.62	1,752.80	11.17	12.31	32.65	1.44	999,329		163	216
	5 km	5.21	9.31	225.90	345.71	2.31	2.69	78.75	3.06	34,043		153	273

Region	Distance from Coral Reefs	Population (millions)		Total Regional Population (millions)†		Proportion of Population to Total regional Population (%)		% increase in Population (2000 - 2020)	Average Population Growth (%, 2000 - 2020)	Area of Land (km^2)		Population Density (per km^2)	
		2000	2020	2000	2020	2000	2020			2000	2020	2000	2020
Middle East	**10 km**	9.91	18.04	313.21	492.79	4.39	5.22	82.10	3.14	71,156		139	254
	30 km	15.84	30.33			7.01	8.77	91.43	3.38	242,181		65	125
	50 km	19.99	37.63			6.38	7.64	88.23	3.28	438,099		46	86
	100 km	35.71	63.83			11.40	12.95	78.74	3.00	964,615		37	66
Pacific	**5 km**	3.35	4.37	8.47	11.38	39.55	38.38	30.38	1.36	72,680		46	60
	10 km	4.13	5.37			48.80	47.17	29.86	1.33	112,595		37	48
	30 km	5.32	6.75	42.35	50.90	12.57	13.26	26.69	1.20	198,226		27	34
	50 km	6.91	8.59			16.32	16.87	24.23	1.10	246,204		28	35
	100 km	8.87	10.97	47.48	58.16	18.68	18.87	23.73	1.07	327,288		27	34
Southeast Asia	**5 km**	38.72	52.25	1,936.80	2,196.82	2.00	2.38	34.93	1.53	195,073	195,094	199	268
	10 km	69.54	90.13			3.59	4.10	29.60	1.31	354,746		196	254
	30 km	188.46	231.60			9.73	10.54	22.90	1.04	852,707	852,729	221	272
	50 km	282.24	352.98			14.57	16.07	25.06	1.13	1,243,281	1,243,303	227	284
	100 km	437.12	558.05	1,942.76	2,204.90	22.50	25.31	27.66	1.24	2,048,954	2,048,976	213	272

* Total Regional Population calculated from total country population extracted from LandScan database

† Area of Land (km^2) calculated from total country area found within distance regions from coral reefs

Table S17. Summary statistics of coral reef countries grouped by income group populations near coral reefs from 5 km to 100 km in 2000 and 2020.

Region	Distance from Coral Reefs	Population (millions)		Total Income Group Population (millions)*		Proportion of Population to Global Population (%)		Percentage increase in Population (2000 - 2020)	Average Population Growth (%, 2000 - 2020)	Area of Land (km²)		Population Density (per km²)	
		2000	2020	2000	2020	2000	2020			2000	2020	2000	2020
Low	**5 km**	7.92	15.00	105.68	174.53	7.49	8.59	89.40	3.28	34,958		227	429
	10 km	11.16	21.38			10.56	12.25	91.55	3.33	70,531		158	303
	30 km	18.35	32.76			17.36	18.77	78.56	2.95	219,549		84	149
	50 km	25.61	44.12	169.82	282.73	15.08	15.60	72.23	2.76	379,203		68	116
	100 km	42.44	67.16			24.99	23.76	58.24	2.33	804,322		53	84
Lower middle	**5 km**	44.06	60.24	1,611.50	2,118.09	2.73	2.84	36.72	1.60	253,922		174	237
	10 km	86.66	111.67			5.38	5.27	28.86	1.29	455,816		190	245
	30 km	207.22	249.98	1,740.34	2,281.48	11.91	10.96	20.63	0.95	1,068,506		194	234
	50 km	305.58	370.68			17.56	16.25	21.30	0.97	1,549,216		197	239
	100 km	474.30	591.60	1,888.46	2,290.06	25.12	25.83	24.73	1.12	2,586,380		183	229
Upper middle	**5 km**	12.78	18.23	1,868.76	2,151.45	0.68	0.85	42.69	1.81	57,444		222	317
	10 km	25.26	35.53			1.35	1.65	40.67	1.73	121,621		208	292
	30 km	69.00	93.25			3.69	4.33	35.14	1.53	446,589		155	209
	50 km	106.63	145.17	1,891.92	2,190.32	5.64	6.63	36.14	1.57	831,766		128	175
	100 km	186.83	252.96			9.87	11.55	35.40	1.54	1,732,223		108	146
High	**5 km**	10.26	13.44	218.46	260.07	4.69	5.17	31.03	1.40	63,573		161	211
	10 km	19.00	25.68			8.70	9.87	35.16	1.55	119,774		159	214
	30 km	39.48	56.17	252.34	299.59	15.65	18.75	42.25	1.80	357,718		110	157
	50 km	47.32	68.00			18.75	22.70	43.72	1.85	613,723		77	111
	100 km	57.10	82.92	257.92	307.46	22.14	26.97	45.23	1.90	1,250,997		46	66

* Total Regional Population calculated from total country population extracted from LandScan database

Table S18. Summary statistics of Small Island Developing States populations near coral reefs from 1 km to 100 km in 2000 and 2018.

Distance from Coral Reefs	Population (millions)		Total SIDS Population (millions)*		Proportion of Population to Global Population (%)		Percentage change in Population (2000 - 2020)	Average Population Growth (%, 2000 - 2020)	Area of Land (km^2)		Population Density (per km^2)	
	2000	2020	2000	2020	2000	2020			2000	2020	2000	2020
5 km	14.09	18.86	50.92	63.56	27.67	29.67	35.85	1.48	111,642		126	169
10 km	23.46	30.13			46.07	47.40	28.63	1.26	182,346		129	165
30 km	37.46	47.86			73.57	75.30	27.14	1.24	3,594,923		104	133
50 km	45.19	55.13			88.74	86.73	20.79	1.00	466,254		97	118
100 km	48.44	59.76			95.13	94.02	21.83	1.06	577,774		84	103

* Total Regional Population calculated from total country population extracted from LandScan database

Table S19. Summary of coral reef countries which have 100% of total population, within distance each distance category in the year 2020.

Distance	**ISO3**	**Country**	**Region**	**Income Group**	**SID status**	**Total Countries**
5 km	ABW	Aruba	Caribbean	High	Yes	20
	AIA	Anguilla	Caribbean	*NA*	Yes	
	ASM	American Samoa	Pacific	Upper middle	Yes	
	BLM	Saint Barthélemy	Caribbean	High	No	
	BMU	Bermuda	Atlantic	High	Yes	
	COK	Cook Islands	Pacific	*NA*	Yes	
	CYM	Cayman Islands	Caribbean	High	Yes	
	FSM	Micronesia	Pacific	Lower middle	Yes	
	KIR	Kiribati	Pacific	Lower middle	Yes	
	KNA	Saint Kitts and Nevis	Caribbean	High	Yes	
	MHL	Marshall Islands	Pacific	Upper middle	Yes	
	MSR	Montserrat	Caribbean	*NA*	Yes	
	NIU	Niue	Pacific	*NA*	Yes	
	NRU	Nauru	Pacific	Upper middle	Yes	
	SXM	Sint Maarten	Caribbean	High	Yes	
	SYC	Seychelles	Indian Ocean	High	Yes	
	TKL	Tokelau	Pacific	Others	No	
	TUV	Tuvalu	Pacific	Upper middle	Yes	
	VGB	British Virgin Islands	Caribbean	High	Yes	
	WLF	Wallis and Futuna	Pacific	*NA*	No	
10 km	ATG	Antigua and Barbuda	Caribbean	High	Yes	15
	BHR	Bahrain	Middle East	High	Yes	
	BRB	Barbados	Caribbean	High	Yes	
	COM	Comoros	Indian Ocean	Low	Yes	
	CUW	Curaçao	Caribbean	High	Yes	

Distance	ISO3	Country	Region	Income Group	SID status	Total Countries
	DMA	Dominica	Caribbean	Upper middle	Yes	
	GRD	Grenada	Caribbean	Upper middle	Yes	
	GUM	Guam	Pacific	High	Yes	
	LCA	Saint Lucia	Caribbean	Upper middle	Yes	
	MAF	Saint-Martin	Caribbean	High	No	
	MDV	Maldives	Indian Ocean	Upper middle	Yes	
	MYT	Mayotte	Indian Ocean	*NA*	No	
	PLW	Palau	Southeast Asia	High	Yes	
	TCA	Turks and Caicos Islands	Caribbean	High	Yes	
	VIR	Virgin Islands, U.S.	Caribbean	High	Yes	
30 km	BES	Bonaire, Sint Eustatius and Saba	Caribbean	*NA*	No	10
	BHS	Bahamas	Caribbean	High	Yes	
	GLP	Guadeloupe	Caribbean	*NA*	Yes	
	MTQ	Martinique	Caribbean	*NA*	Yes	
	MUS	Mauritius	Indian Ocean	Upper middle	Yes	
	NCL	New Caledonia	Pacific	High	Yes	
	PRI	Puerto Rico	Caribbean	High	Yes	
	SGP	Singapore	Southeast Asia	High	Yes	
	VCT	Saint Vincent and the Grenadines	Caribbean	Upper middle	Yes	
	WSM	Samoa	Pacific	Upper middle	Yes	
50 km	FJI	Fiji	Pacific	Upper middle	Yes	5
	JAM	Jamaica	Caribbean	Upper middle	Yes	
	REU	Réunion	Indian Ocean	*NA*	No	
	VUT	Vanuatu	Pacific	Lower middle	Yes	

Distance	ISO3	Country	Region	Income Group	SID status	Total Countries
	SLB	Solomon Islands	Pacific	Lower middle	Yes	
100 km	BRN	Brunei	Southeast Asia	High	No	10
	CUB	Cuba	Caribbean	Upper middle	Yes	
	DJI	Djibouti	Middle East	Lower middle	No	
	DOM	Dominican Republic	Caribbean	Upper middle	Yes	
	HKG	Hong Kong	Southeast Asia	High	No	
	HTI	Haiti	Caribbean	Low	Yes	
	MAC	Macao	Southeast Asia	High	No	
	PHL	Philippines	Southeast Asia	Lower middle	No	
	QAT	Qatar	Middle East	High	No	
	TLS	Timor-Leste	Southeast Asia	Lower middle	Yes	

Figure S12. Bump graph displaying top 5 countries ranked by highest total population from 2000 to 2020 at (a) 5 km, (b) 10 km and (c) 30 km, (d) 50 km, and, (e) 100 km from coral reefs.

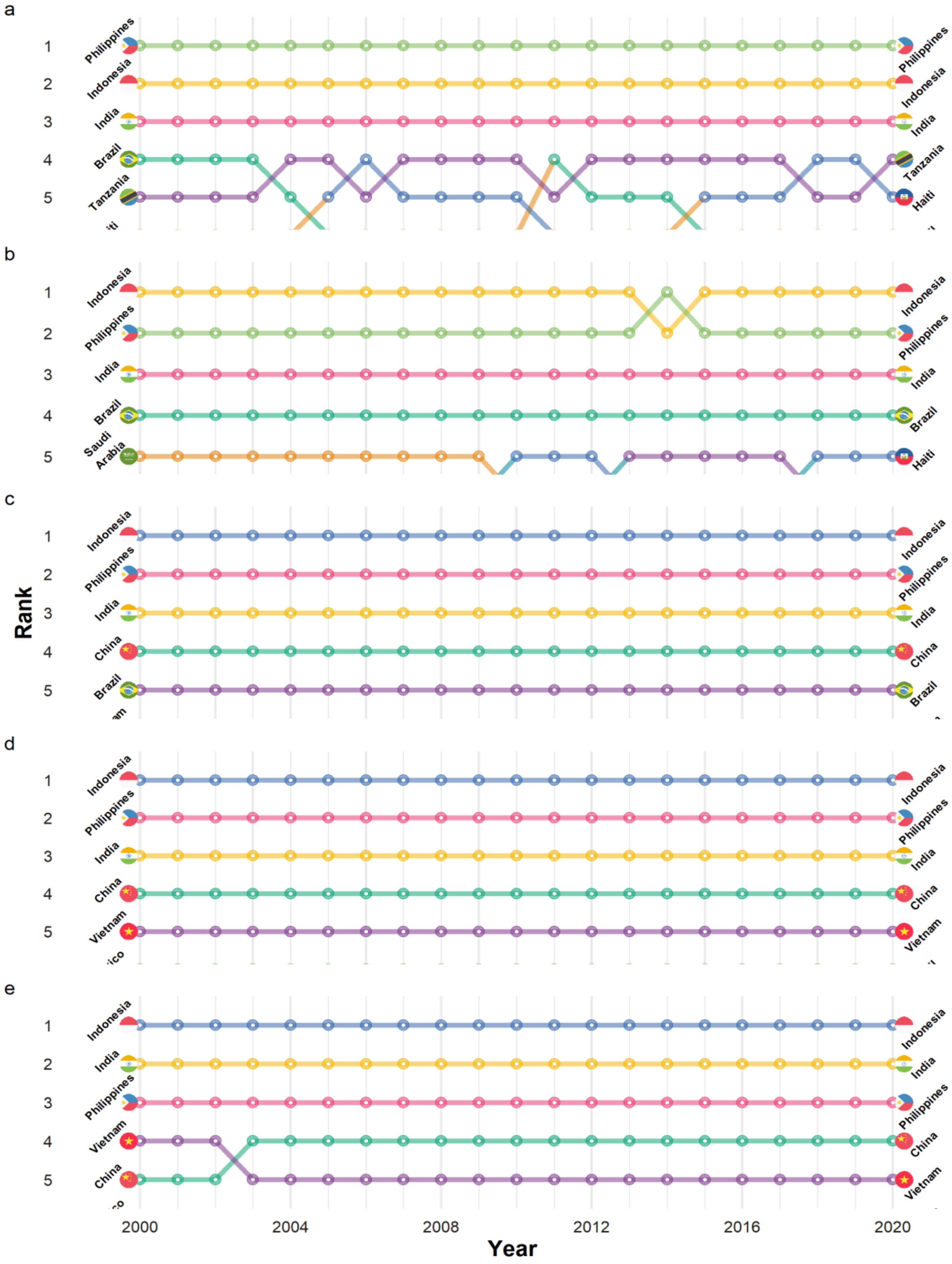


Figure S13. Bump graph displaying top 5 countries ranked by highest population density from 2000 to 2020 at (a) 5 km, (b) 10 km and (c) 30 km, (d) 50 km, and, (e) 100 km from coral reefs.

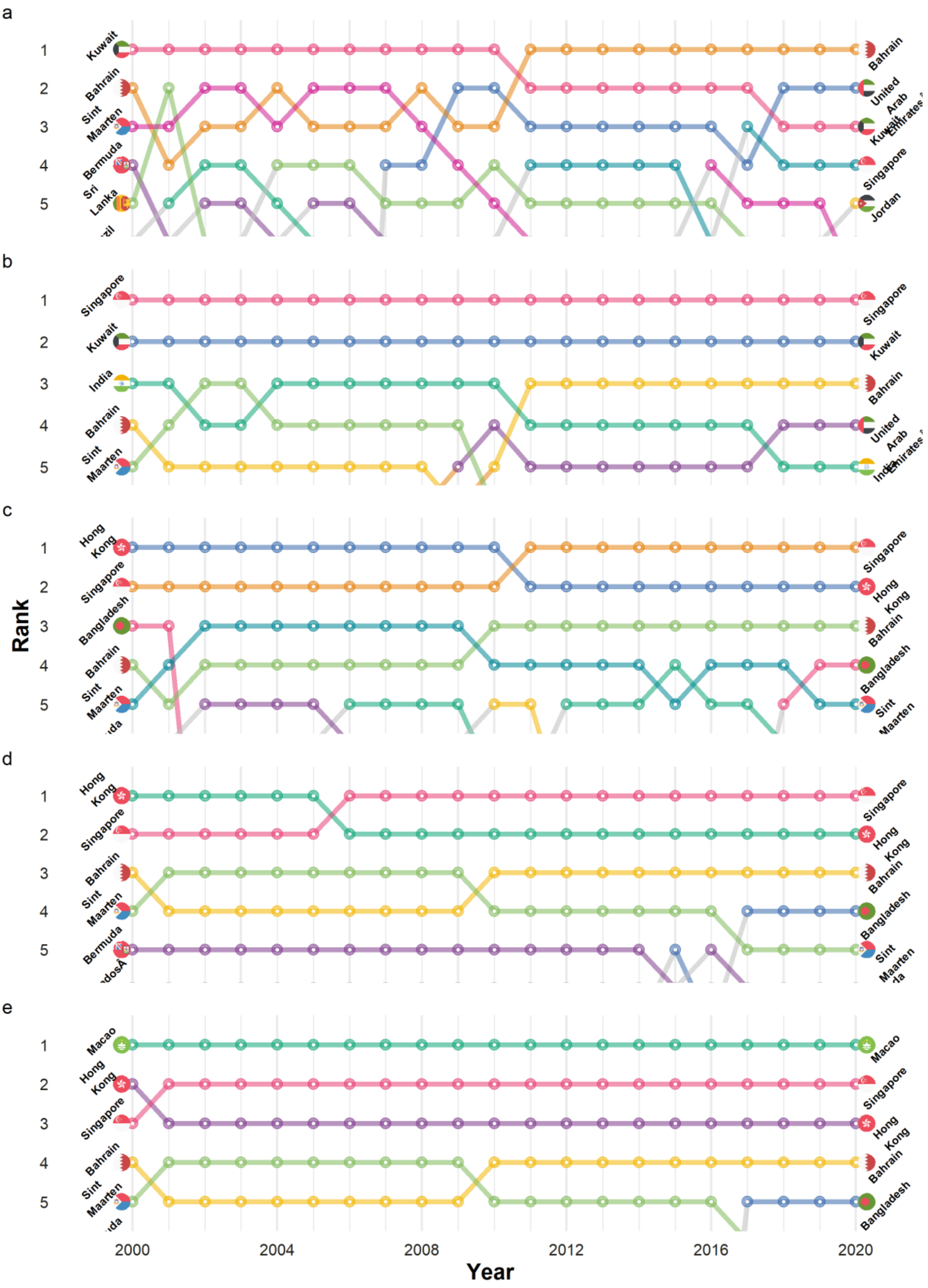


Figure S14. Global population change of people living within 5 km, 10 km, 30 km, 50 km, and 100 km from coral reefs between 2000 to 2020. Dashed line is the average rate of growth over time at each distance. Solid black line represents the world annual population growth (%) taken from (The World Bank, 2018).

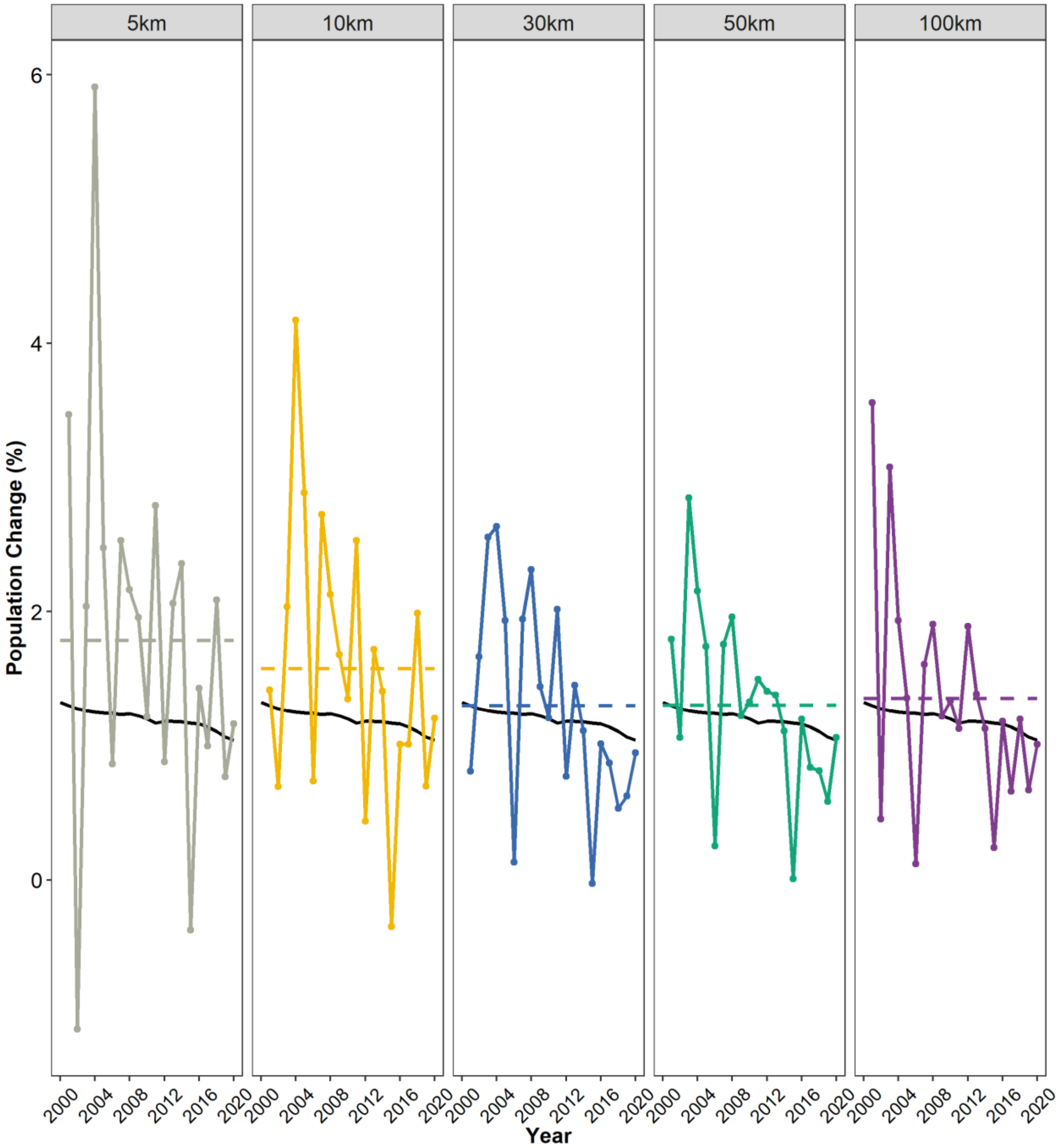


Figure S15. Regional population change (%) of people living within 5 km, 10 km, 30 km, 50 km, and 100 km from coral reefs between 2000 to 2018. Dashed line is the average rate of growth over time at each distance grouped by region. Note varying scales.

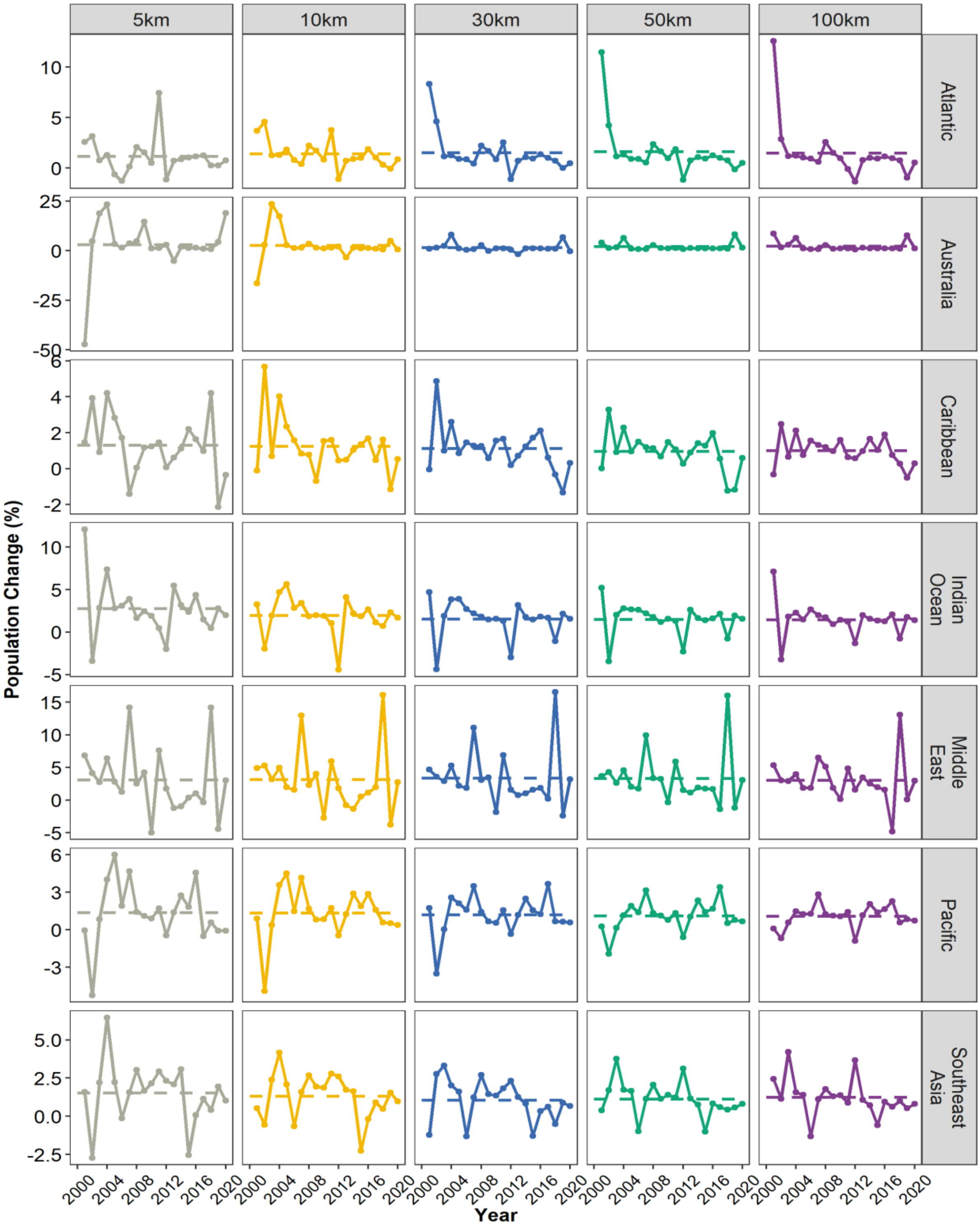


Figure S16. Income group population change (%) of people living within 5 km, 10 km, 30 km, 50 km, and 100 km from coral reefs between 2000 to 2020. Dashed line is the average rate of growth over time at each distance grouped by income group.

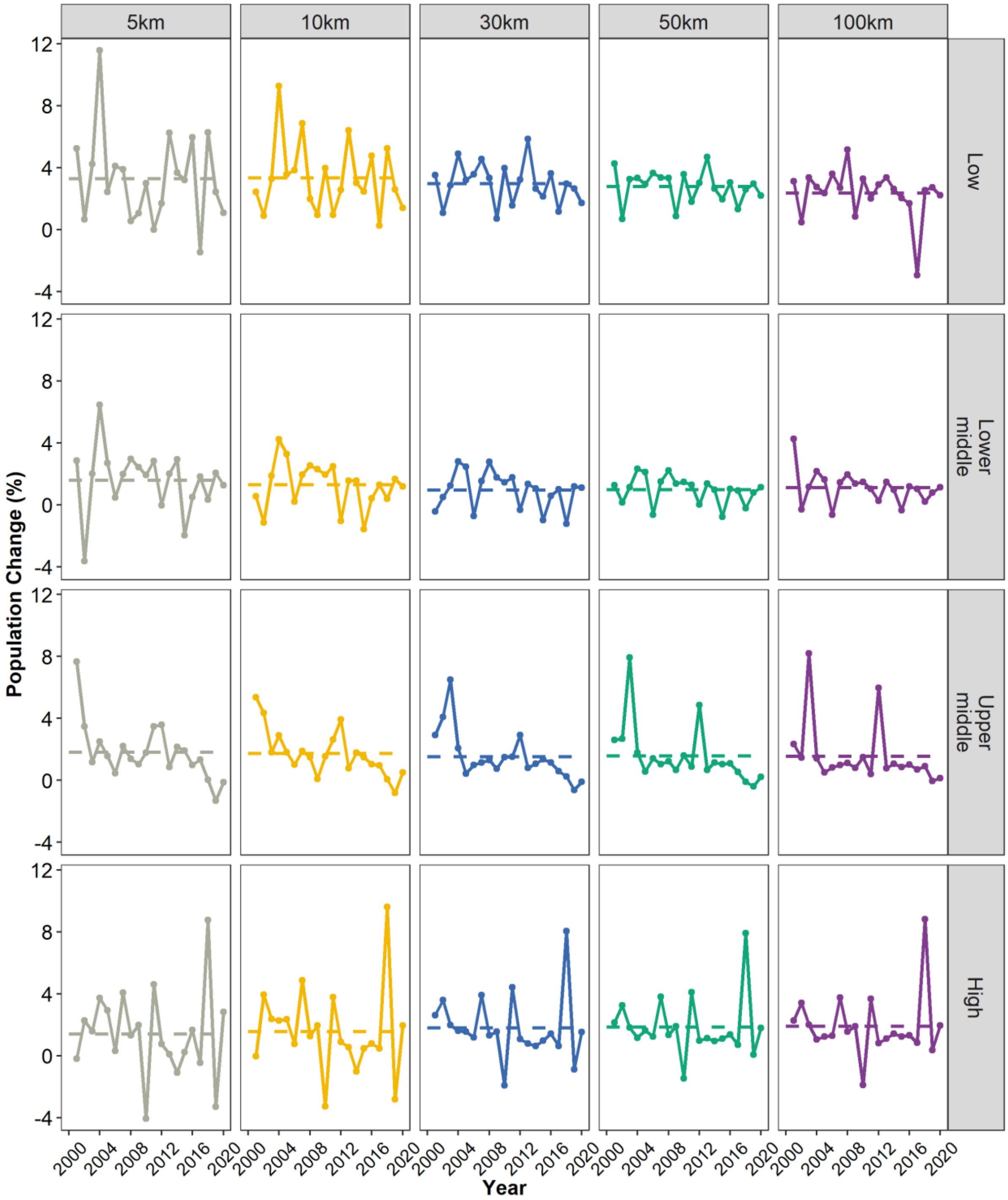


Figure S17. SIDS population change of people living within 5 km, 10 km, 30 km, 50 km, and 100 km from coral reefs between 2000 to 2020. Dashed line is the average rate of growth over time at each distance.

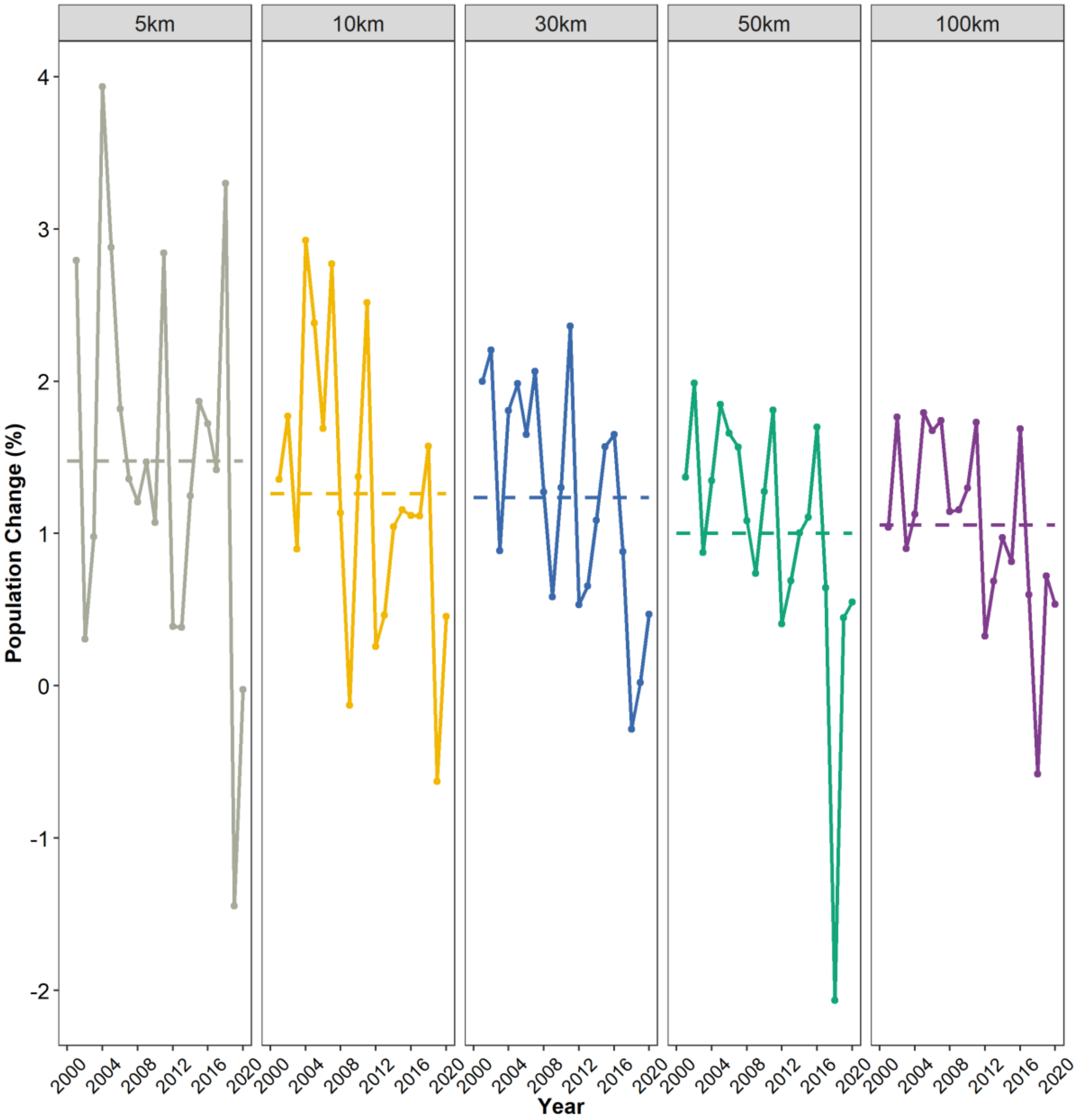


Figure S18. Map of buffers created around (a) Caribbean, (b) the Middle East, (c) Australia, (d) the Indian Ocean, (e) Southeast Asia, (f) the Atlantic and (g) the Pacific regions of coral reefs (purple) at 5 km, 10 km, 30 km, 50 km, and, 100 km.

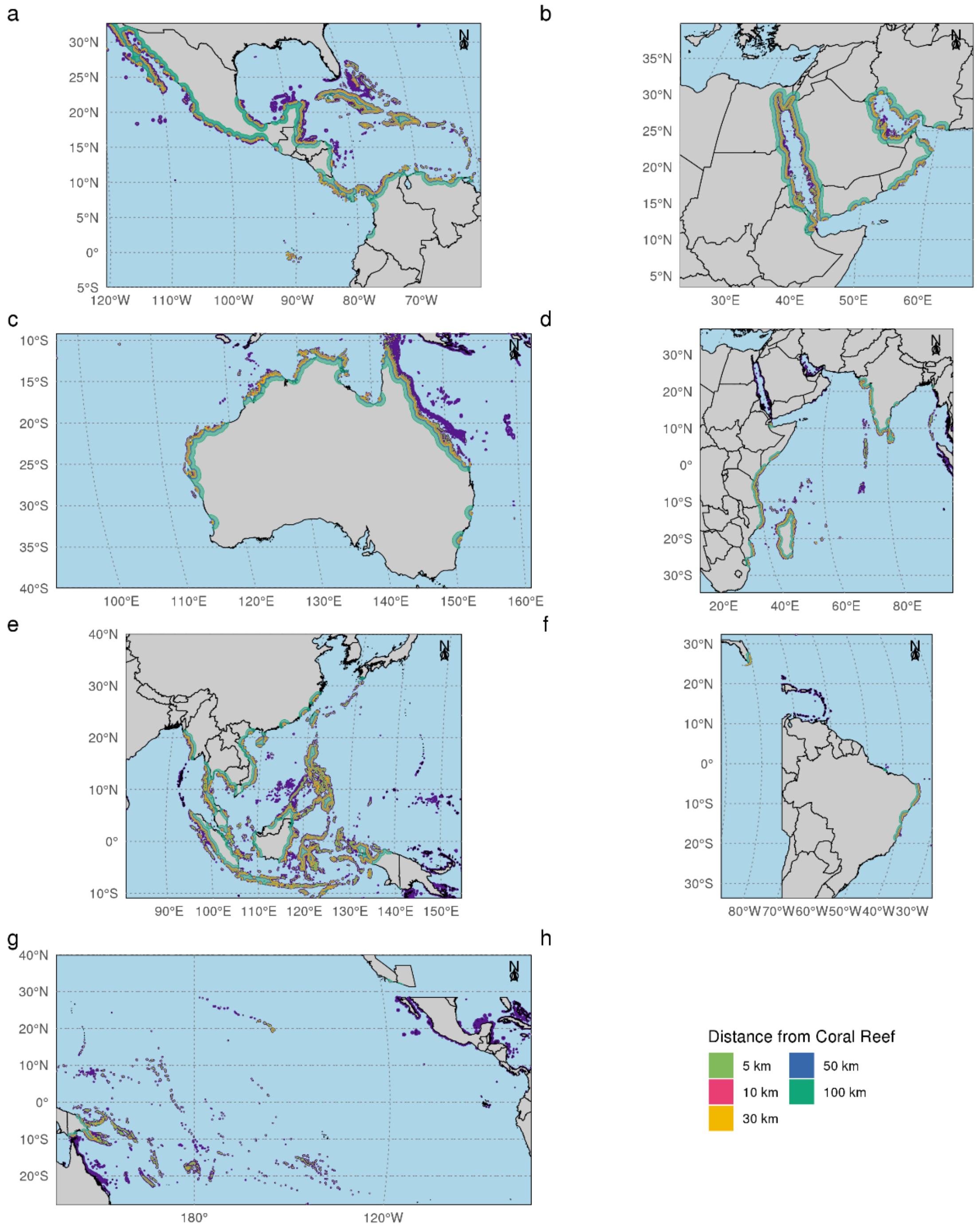
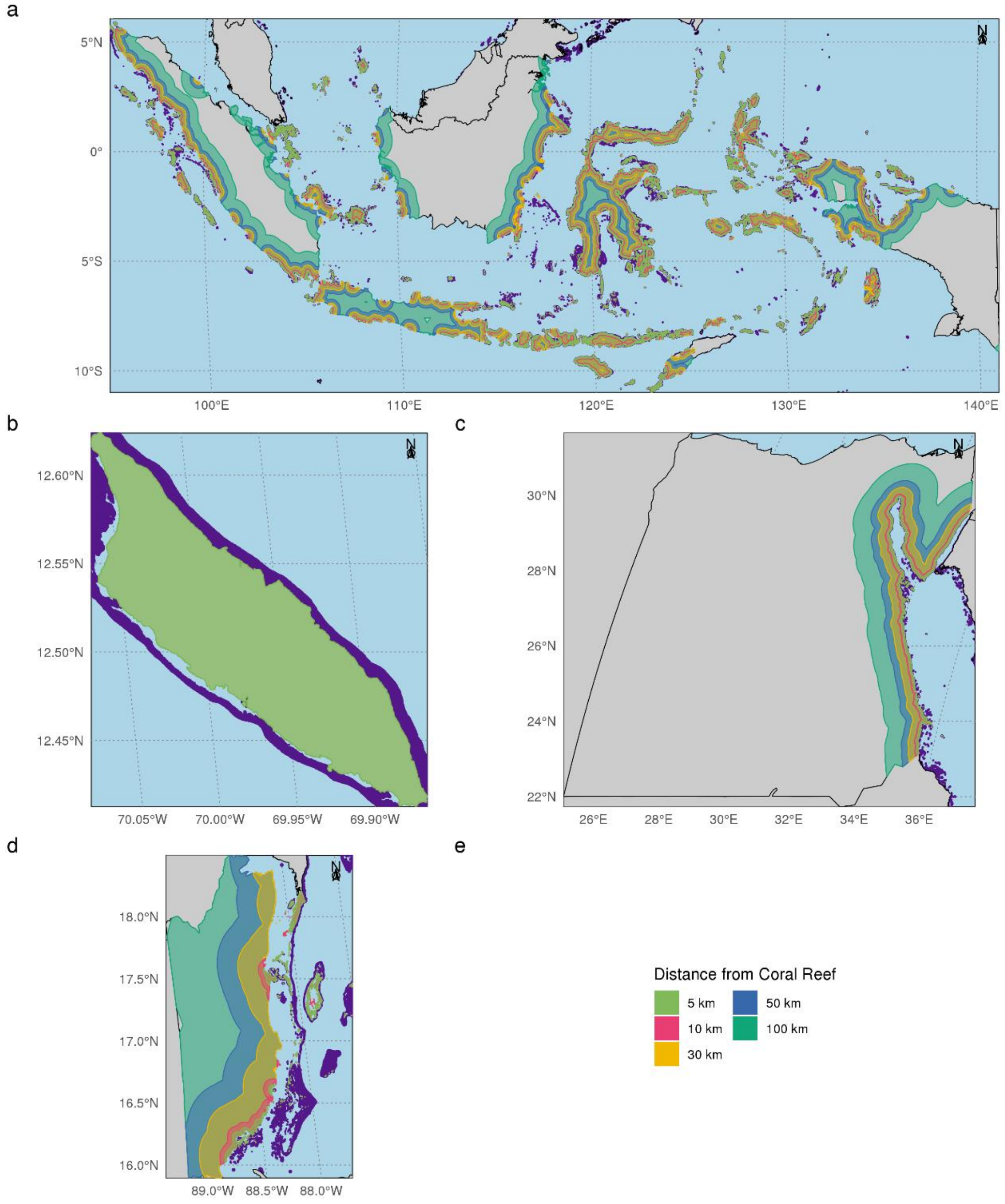


Figure S19. Map of buffers created around (a) Indonesia, (b) Aruba, (c) Egypt, and (d) Belize coral reefs (purple) at 5 km, 10 km, 30 km, 50 km, and, 100 km.



Supplementary Information References

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Chapter 3: Rethinking assessment methods of human dependency on coral reef ecosystems

Abstract

Understanding human dependency on coral reefs and its complexities and nuances is very challenging. We developed a conceptual framework for human dependency on coral reefs, using an indicator approach within four pre-defined categories: fisheries, tourism, nutrition, and coastal protection. Using multiple methodologies, we present how hybrid learning methods can facilitate the assessment of human dependency on coral reefs. Firstly, we created a human dependency index based on rank of coral reef countries (min-max normalised) within and across dependency categories. Further analyses using hybrid learning techniques revealed the driving factors of dependency on coral reefs and established human dependency “profiles”. Human dependency profiles presented “how” countries were experiencing dependency through classification, and which indicators influenced this the most from linear discriminant analyses on principle components. We managed understand how different indicators presents variation in human dependency; within fisheries we found economic and employment factors to drive much of the dependency we would expect, and reef health could be more indicative of nutritional indicators when analysing overall human dependency. Utilising indicator data, presented opportunities to create varying profiles of dependency, where dependency was described along scales of economic benefits, or at levels of different risk, resulting in a risk matrix for nutritional dependency on coral reefs. Additionally, we managed to capture the sensitivity of methods, and care must be taken in interpretation due to the caveat of missing data and missing data imputation, In summary we have created a framework that is adaptable to different scales (global, regional, and national data), types of data and future improvements of available datasets. This paper hopes to encourage the field to move away from linear thinking about human dependency on a high to low scale, and towards an approach that considers the different categories of dependencies individually. We believe this novel framework will bring more informed decision-making and risk assessments to humans and coral reef ecosystems.

Keywords: Human dependency conceptual framework, hybrid learning, modelling, human dependency profiles, coral reefs, coral reef management, human risk analysis.

Introduction

Ecosystems and humans are intrinsically linked, and people often derive benefits and goods via ecosystem services (Hernández-Blanco et al., 2022; Hoegh-Guldberg et al., 2019; Taylor et al., 2019) - a phenomena referred to as 'human well-being'. How human dependency has been assessed varies greatly; previous studies have taken an indicator approach (Guo et al., 2010; Pendleton et al., 2016), mapping (Selig et al., 2018), two-dimensional dynamical modelling (Cazalis et al., 2018), and applying machine learning through Bayesian modelling (Balbi et al., 2019) to human dependency assessments.

Understanding human dependency on ecosystems is often a complex task, buffeted by a multitude of interacting factors. Cazalis et al. (2018) states "the ability of the human population to continue growing depends strongly on the ecosystem services provided by nature". Conversely, we understand that humans have also been a cause of degradation and threats to ecosystems with many studies having this as the focus (Cannon et al., 2019; Cowburn et al., 2018; Guest et al., 2018; Hamilton et al., 2017; Suchley & Alvarez-Filip, 2018). Although some research has found contrasting evidence, for example Baumann et al. (2022) found that coral reefs with greater human development may recover faster than their remotely located counterparts; and Cinner et al. (2022) reveals that moderate human development increased probabilities of encountering top predators, fish biomass and fish trait diversity compared to high or low human development.

There is a desire to understand complex social-ecological systems to assess risk, improve management and create policies that protect the most vulnerable ecosystems and human populations. There are presently few studies which assess human dependency explicitly on coral reef ecosystems (Burke et al., 2011; Pendleton et al., 2016). This paper hopes to encourage the field to move away from linear thinking about human dependency on a high to low scale, and towards an approach that considers the different categories of dependencies individually; this is important as clearly some coral reefs, nations, and/or regions are subject to multiple, competing, human dependencies that have different impacts on the human populations that depend upon them. For example, countries may not only rely on coral reefs for nutritional needs, but also as economic income in terms of fisheries and/or tourism.

Our study aims to investigate human dependency on coral reefs by adapting methods from Pendleton et al. (2016) of ranking human dependency indicators, alongside novel hybrid learning techniques (a combination of unsupervised and supervised learning) to create a more holistic view of dependency. This study models profiles of human dependency on coral reefs as a complement to current methods of ranking z-scores. Using openly accessible data we have developed an indicator based on a human dependency conceptual framework that is adaptable from global to regional and national levels.

Methods

The human dependency framework was defined from literature and adapted from ecosystem dependency studies (Pendleton et al., 2016; Rogers, 1979; Selig et al., 2018), with dependency categories in this study of fisheries, tourism, nutrition, and coastal protection. Following an indicator approach, for each human dependency category, representative indicator data were collected (Table 20).

Data was obtained to relate as closely as possible to coral reef ecosystems and transformed for each country where necessary to ensure relative comparisons between countries. This was achieved by extracting data that identified as coral reef-related during processing or extracted from studies which focused on coral reef ecosystems. However, there are indicators that were not linked with corals reefs, but were associated with countries that are within 100 km of coral reef ecosystems. For example, data within the nutrition category was extracted from FAO databases which are not explicitly related to coral reefs. This was due to limited availability of global data for nutrition human dependency category on coral reefs.

Table 20 presents a summary of all the indicators applied into the conceptual human dependency framework. Indicators were selected based on a number of factors, where the main limitations were accessing global scale data representative of coral reef countries. However, within each category a minimum of three indicators were collected to provide a more representative analyses to human dependency.

Table 20. Summary of indicators in each human dependency category.

Human dependency category	Indicator Name	Description	Source
Fisheries	Pct_mean_reef_val_GDP	Proportion of mean reef fisheries value (mean value between 1950 – 2019) to country total GDP ($USD 2019): Mean value of reef catch data filtered by coral reef functional groups. "small reef assoc. fish (<30 cm)", "medium reef assoc. fish (30 - 89 cm)", "large reef assoc. fish (>=90 cm)", by EEZ, from 1950 to 2019 extracted from Seas Around Us catch reconstruction database. Country total GDP ($USD) was extracted from UNSTATS, World Bank and IMF for 2019.	(International Monetary Fund, 2021; Pauly et al., 2020; The World Bank, 2022; United Nations, 2021a)
	MeanReef_bio_area_km2	Mean reef fish biomass (t/km^2) of country coral reef area: Mean landings (tonnage) of reef catch data filtered by coral reef functional groups. "small reef assoc. fish (<30 cm)", "medium reef assoc. fish (30 - 89 cm)", "large reef assoc. fish (>=90 cm)", by EEZ, from 1950 to 2019 extracted from Seas Around Us catch reconstruction database. Coral reef area (km^2) for each country taken from Sing Wong et al. (2022)	(Pauly et al., 2020; Sing Wong et al., 2022)
	Pct_fishermen_100	Proportion of coral reef fishermen to coral reef population at 100 km in 2010: Coral reef fishermen estimations from Teh et al. (2013) and coral reef populations at 100 km in 2010 from Sing Wong et al. (2022).	(Sing Wong et al., 2022; Teh et al., 2013)
Tourism	pct_reef_spending_GDP	Reef tourism as proportion of GDP	(Spalding et al., 2017)

	Pct_reef_tourists	Proportion of reef tourists arrival to all tourist arrivals (international and domestic)	
	pct_reef_spending_tour	Reef visitor expenditure as proportion of total tourism expenditure	
Nutrition	MicronutDensityScore_W	Micronutrient density (%) of five micronutrients (calcium, iron, zinc, selenium and vitamin A) adapted from Maire et al. (2021), using only coral reef functional groups. "small reef assoc. fish (<30 cm)", "medium reef assoc. fish (30 - 89 cm)", "large reef assoc. fish (>=90 cm)", by EEZ, from 1950 to 2019 extracted from Seas Around Us catch reconstruction database.	(Maire et al., 2021; Pauly et al., 2020)
	mean_PII	Mean prevalence of inadequate intake of 4 key micronutrients (%): calcium, iron, vitamin A and zinc adapted from Maire et al. (2021) and Beal et al. (2017).	(Beal et al., 2017; Maire et al., 2021)
	Prev_food_insec	Prevalence of moderate/severe food insecurity (%) in 2020 for each country. An indicator for SDG goal 2: Zero Hunger.	(FAO, 2021)
	Prev_under_nour	Prevalence of undernourishment (%) in 2020 for each country. An indicator for SDG goal 2: Zero Hunger.	(FAO, 2021)
Coastal Protection	Pct_pop_LECZ_50	Proportion of Low Elevation Coastal Zone (LECZ) population to 50 km coral reef population in 2015: LECZ population extracted from LECZ v.3 (Center for International Earth Science Information Network - CIESIN - Columbia University & CUNY Institute for Demographic Research - CIDR - City University of New York, 2021) and 50 km coral reef population from 2015 from Sing Wong et al. (2023)	(CIESIN - Columbia University & CIDR - City University of New York, 2021; Sing Wong et al., 2022)

	Annual_averted_damages_GDP	Annual averted damages ($USD) with coral reefs: The values are the difference in expected damages to built capital with and without reef for 100-year events, relative to country GDP.	(Beck et al., 2018)
	A_km2	Annual area avoided flooded (km^2) with coral reefs	(Beck et al., 2018)

Data collection

Fisheries

Reef fish catch data was collected for coral reef countries by Exclusive Economic Zone (EEZ), and organised by functional groups for value and tonnage of catch between the years 1950 to 2019 from the Seas Around Us catch reconstruction database (Pauly et al., 2020) using the r package 'seasaroundus' v.1.2.0 (Chamberlain & Scott Reis, 2017). Using reef fish functional groups, classified as, small reef-associated fish (<30 cm), medium reef-associated fish (30 - 89 cm), and large reef-associated fish (>=90 cm), the mean value ($USD) and biomass (t) for each coral reef country was calculated

Country total GDP ($USD 2019) data was collected from the United Nations Statistics Division, National Accounts Main Aggregates Database (United Nations, 2021a). Coral reef area (km^2) and coral reef populations at 100 km from coral reefs was obtained from Sing Wong et al. (2022). Number of coral reef fishermen was taken from the study by Teh et al. (2013).

The mean value of reef fisheries and total country GDP were used to calculate the proportion of mean reef fisheries value to total country GDP. Coral reef area and mean reef fish biomass was calculated for each country. The coral reef population was used to calculate the proportion of coral reef fishermen, using populations at 100 km, to encompass those that may depend on coral reefs for livelihoods. The Marshall islands, resulted in over 100% of coral reef fishermen to coral reef populations at 100km therefore were excluded from further analysis with proportion of coral reef fishermen indicator.

Tourism

Tourism on coral reef indicators were taken from Spalding et al. (2017), supplementary material. These indicators included reef tourism as a proportion of total country GDP, proportion of reef tourists arrivals to all tourist arrivals (international and domestic), and reef visitor expenditure as a proportion of total tourism expenditure. These data were collected for further analysis, as this study calculated the global value and distribution of coral reef tourism from global tourism statistics, social media, and crowd-sourced datasets. Indicators for the USA were split into Florida and Hawaii, we retained Florida values to represent tourism indicators for the USA as we believed it would be more representative of the country as a whole.

Nutrition

Micronutrient density (%) of five micronutrients data was calculated using an adapted method and data from Maire et al. (2021), where SAU fisheries catch data (Pauly et al., 2020) was constrained to coral reef countries and reef only associated fish defined by functional groups of small reef-associated fish (<30 cm), medium reef-associated fish (30 - 89 cm), and large reef-associated fish (>=90 cm). This indicator reflects the availability of micronutrients that coral reefs may provide for populations.

Mean prevalence of inadequate intake of 4 key micronutrients (%) was adapted from Maire et al. (2021) with data obtained from a study by Beal et al. (2017) for coral reef countries. Inadequate intake of micronutrients has been described as “hidden hunger” (Beal et al., 2017) and can reflect the necessity of coral reef micronutrient availability.

Two sustainability development goal (SDG) indicators for goal 2 (Zero Hunger) were collected for coral reef countries from (FAO, 2021), the prevalence of moderate/severe food insecurity (%) which reflects the difficulties in accessing food, and, the prevalence of undernourishment (%) which reflects hunger for in terms of receiving insufficient dietary requirements coral reef countries in 2020.

Coastal protection

Human dependency on coastal protection was represented by indicators collected from Beck et al. (2018) supplementary material which investigated the global flood protection savings provided by coral reefs. Indicators adapted from this study included, annual expected area avoided flooded (km^2) with coral reefs (the top 1m), and annual averted damages, which describes the difference in built capital flooded with and without reefs for 100-year events, which was calculated by:

$$Annual\ averted\ damages\ = \frac{(BC\_USD11 - \ BCD50\_USD11\ )}{Total\ country\ GDP}$$

Where “BC_USD11” is the annual expected built capital avoided flooded ($) and “BCD50_USD11” is the annual expected built capital avoided damaged, assuming 50% of damage for 1m of flood height ($), and, total GDP of countries ($USD 2011).

Additionally, mean populations at low elevation coastal zones under 10 m sea level within 50 km of coral reefs were extracted from Low Elevation Coastal Zone (LECZ) Urban-Rural Population and Land Area Estimates, Version 3 (CIESIN & CIDR, 2021) using 50 km coral reef buffer (Sing Wong et al., 2022). The LECZ spatial dataset was overlaid using 100 and 50km buffers from coral reefs (Figure S28 a & b), and clipped where low elevation zones intersected with buffers (Figure S28c & d). With 50 km with coral reef low elevation zones used to extract LECZ populations, as this reflected best areas of low elevation to coral reefs.

Data analysis

Relative human dependency was calculated across all categories (fisheries, tourism, nutrition, and coastal protection) and overall human dependency incorporates all categories at coral reef country level. Coral reef countries were obtained from literature and compiled as a comprehensive dataset defined by countries within 100 km radius of coral reefs. Note that data for the USA was sometimes divided into states such as Florida and Hawaii, for these states the data was aggregated for an overall United States country level.

Two methods to model human dependency 1) adapted from Pendleton et al. (2016), where human dependency was calculated by averaging the min-max normalised indicator data to create a human dependency on coral reefs index and, 2) hybrid learning techniques were applied to create human dependency profiles.

Human Dependency on Coral Reefs Index

The Human Dependency on Coral Reefs Index (from herein HDCRI) was calculated from normalised indicator data within human dependency categories for each coral reef country. Indicator data within each category was first normalised between countries, this was to ensure that all countries were comparable within each and across indicators. Normalisation of indicators were calculated using the equation for min-max normalisation, which rescaled data between 0 to 1:

$$Xnormalised = \frac{X - Xmin}{Xmax - Xmin}$$

HDCRI for each human dependency category was calculated for countries which had two or more indicator data collected, where normalised indicators were averaged for each coral reef country. Overall HDCRI was calculated for countries that had two or more indicator data available across all human dependency categories. Using the same process as within category human dependency, the overall HDCRI was calculated by averaging all available indicator data for each coral reef country.

The HDCRI was further transformed for enhanced data visualisation and interpretability by log transformation. To handle zero values generated from indicator data and normalisation in HDCRI calculations, a constant was added to all values prior to log transformation. Log transformation of HDCRI were calculated using the formula:

$$\log(y + c)$$

Where "*y*" is the HDCRI value, and "*c*" is a constant added to all values within each HDCRI category and is determined as the half the minimum non-0 value. A custom function was created to easily apply this for HDCRI in r, and was as follows:

```
log0.5 <- function(x){
  return(log(x + min(x[x>0])/2))
                    }
```

Human dependency profiles

In order to create the human dependency profiles, a combination of unsupervised and supervised learning analyses were applied, known as hybrid learning. The structure of hybrid learning uses unsupervised learning followed by supervised learning methods to model human dependency and classify countries into groups based on the indicator data.

A principal component analysis (PCA) was applied first, to reduce dimensions and extract features with minimum loss of information (Alpaydin, 2010), that best explain the most variance between groups in relation to human dependency indicators. The principal component analyses (PCA) were conducted using the ‘pca()’ function from the ‘pcaMethods’ v.1.92.0 package in R (Stacklies et al., 2007).

Specifically a probabilistic PCA (PPCA) was used to take into account the presence of missing data within human dependency indicators, which utilises an expectation-maximization (EM) approach for PCA combined with a probabilistic model (Stacklies et al., 2007). Indicator data was scaled and centred using the ‘prep()’ function, and cross-validated using the ‘kEstimate()’ function applied with the normalised root mean square error of prediction (NRMSEP) to estimate optimal principal components for missing value estimation (Stacklies et al., 2007).

This was followed by unsupervised clustering methods, to classify coral reef countries into groups based on the principal components within each category. K-means clustering and agglomerative hierarchical clustering methods were applied, to see variations between methods, where groups are based on similarity (k-means) and dissimilarity (hierarchical) measures. Where Ward’s minimum variance method is applied to hierarchical clustering.

Principal component (PC) scores within human dependency indicators were applied to k-means clustering (KC) using the ‘fviz_nbclust()’ function in the ‘factoextra’ v.1.0.7 package (Kassambara and Mundt, 2020; parameters applied were, “wss"- for total within sum of square method, using Euclidean distances); and hierarchical clustering (HC) using the ‘agnes()’ function in the ‘cluster’ v.2.1.4 package (Maechler et al., 2021; agglomerative clustering using Ward's method) to determine clusters within the data. Optimum clusters within each human dependency category including overall human dependency were determined using the ‘NbClust()’ function from the ‘NbClust’ v.3.0.1

package in R (Charrad et al., 2014), using the “kmeans” method for k-means clusters, and “ward.D” method for hierarchical clusters. Note that the minimum and maximum number of clusters were set at 2 and 5 respectively for categories and 3 and 12 respectively for overall human dependency. Number of clusters were decided on a majority rule, however, if there was a tie, the higher number of clusters were selected for the final analyses.

Finally a supervised learner was utilised in the form of linear discrimination analysis on principal components (LADPC). This was applied to both the k-means and hierarchical clusters as the predefined grouping labels for training the LADPC model. The trained model was then used to predict groups of coral reef countries using the indicator data with all human dependency categories. Predicted vs. observed groups from clustering methods were then plotted with the PPCA results, for coral reef countries and variables.

The linear discriminant analyses were conducted using the ‘LDA()’ function from the ‘flipMutivariates’ v.1.1.9 package in R (Displayr, 2023), with methods for missing data set as “Imputation (replace missing values with estimates).

These methods were chosen to facilitate inference of human dependency on coral reefs using relatively high dimensional data that was initially collected or generated for other purposes. Additionally, by using two methods of clustering we can see how variation of human dependency is modelled using different approaches and how well they performed in predicting human dependency profiles. Finally, we are able to plot the variables (indicator data) and quantify how they drive variation between human dependency profiles and the contribution to that variation.

Mapping

Maps of human dependency were created in R using the ‘ggplot2’ v.3.3.0 package (Wickham, 2016). Coral reef distribution was obtained from the latest coral reef map provided by UNEP-WCMC 2018 v.4 (UNEP-WCMC et al., 2018).

Results

Human Dependency on Coral Reefs Index (HDCRI)

In the HDCRI analyses, within each human dependency category the number of coral reef countries included varied due to data availability and is summarised in Table 21 and details of countries included in HDCRI analyses with all categories and the number of indicators included for calculations summarised in Table S24.

Table 21. Summary of the number coral reef countries included in each human dependency category for HDCRI analyses.

Human dependency category	Number of coral reef countries
Fisheries	100
Tourism	78
Nutrition	79
Coastal Protection	86
Overall	54

The results of the HDCRI analyses, were scaled between 0 and 1, with scores of 0 depicting countries of lowest relative dependency and 1 highest for coral reef countries within human dependency categories. Figure 20 presents a heatmap of HDCRI scores for coral reef countries within each human dependency category.

The normalisation method applied to indicator data allows for much more representative comparisons within categories, than between categories of human dependency. However, broad trends are present across human dependency categories, where overall and nutritional dependency presents all coral reef countries on the higher end of the HDCRI, compared to fisheries, tourism and coastal protection.

This may suggest that nutrition and overall dependency on coral reefs is generally observed as high. On the other hand it may be that nutrition is a major driving force of high dependency on coral reefs, though, four out of the top 10 ranked countries (Somalia, Swaziland, Timor-Leste and Yemen) for nutrition, did not have enough indicators for an overall dependency calculation. Therefore, would not have contributed to the HDCRI rankings of overall dependency.

Figure 21e shows that countries of the highest dependency on nutrition from coral reefs are located in mainly on the East coast of Africa, followed by Asia and Southeast Asia. The United States presents as the lowest dependency on nutrition from coral reefs, followed by Brazil. However, high dependency on nutrition is distributed homogeneously across coral reef countries, with little variation between the HDCRI. Nutritional dependency affected the least amount of people (66 million people; Table 22) compared to all other categories, it must be noted that within the top 10 countries is Swaziland, which only falls within coral reef countries at 100 km.

Fisheries and coastal protection presents mid to low HDCRI for the majority of countries, where tourism shows a mix of HDCRI but with the majority of countries falling in the higher end of HDCRI. Higher dependency on fisheries is generally found in Southeast Asia and the Pacific, in addition to South Africa and Ecuador (Figure 21b). The distribution of high dependency on tourism from coral reefs was located primarily on small islands and archipelagos located in Southeast Asia, the Caribbean and Indian Ocean (Figure 21c). Bonaire, Maldives, Palau and Cayman Islands were the top 4 ranking countries for tourism dependency from coral reefs (Table 22), with the population of the top 10 countries at 895,465 people, which was reached at 30 km from coral reefs and is only 6000+ people more than the total population at 5 km from coral reefs in 2020 at 889,429 people.

Highest human dependency on coastal protection was found mainly in Southeast Asia and countries boarding the Caribbean Sea (Figure 21d). With the top 5 ranking countries of Philippines, Belize, Cuba, Indonesia and The Bahamas. Notably, the United States ranked in at 6th for coastal protection dependency (Table 22), with this category affecting the most people ranked in the top 10 countries of around 414 million people in 2020.

Overall HDCRI was calculated for only 53 coral reef countries, due to lack of indicators available across the human dependency categories. Exclusion of countries, that did not have more than two indicators represented in each category was to reduce any potential bias from individual indicators that may be driving high variance within categories. Thus, we wanted to ensure that there was more representative data for each category to calculate an overall HDCRI for countries. Resulting in a global homogenous distribution of high dependency for coral reef countries (Figure 21a).

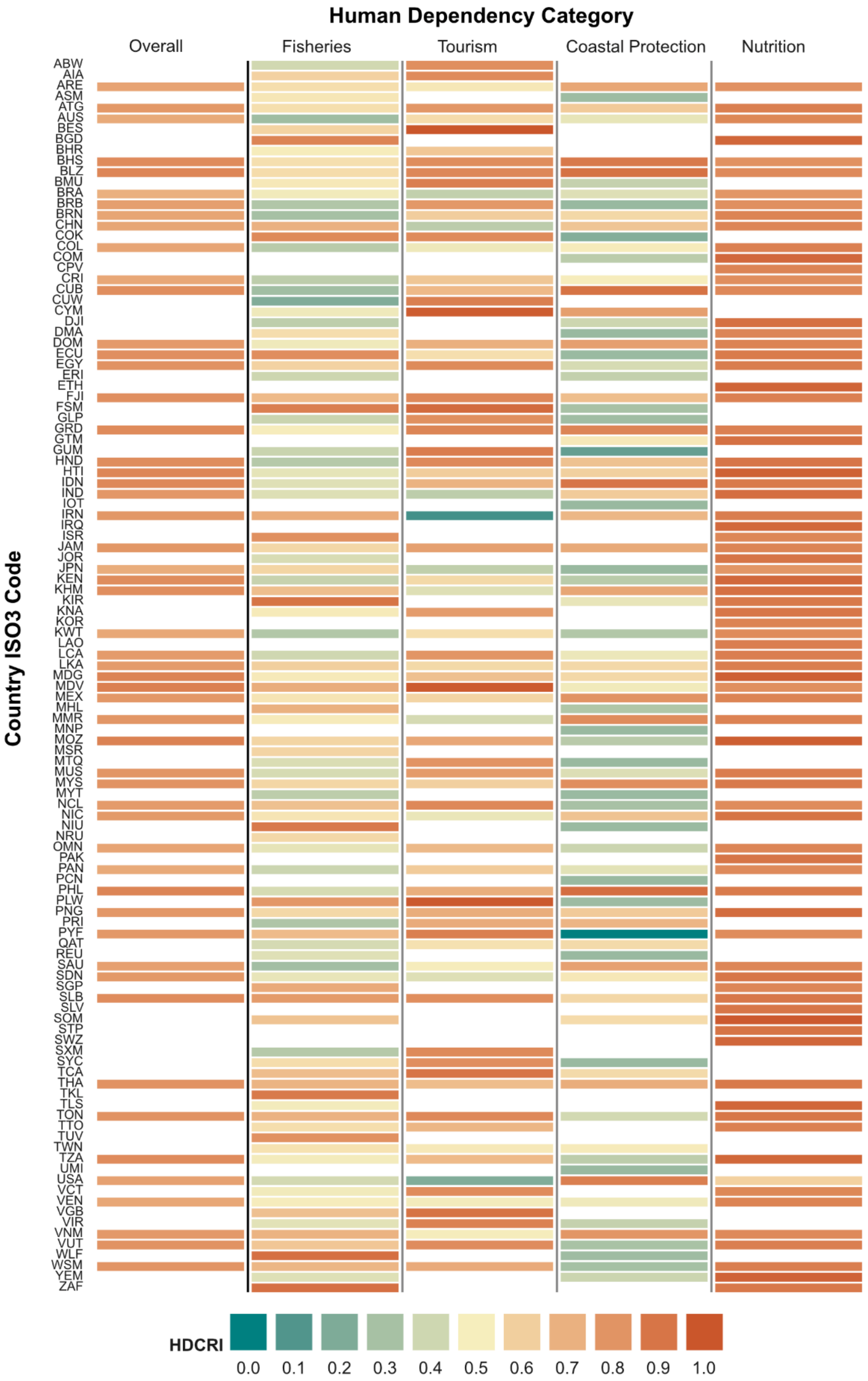

Figure 20. Heatmap human dependency on coral reefs index (HDCRI) for coral reef countries within each category; fisheries, tourism, coastal protection, nutrition, overall (labelled by ISO code). White spaces = NA values.

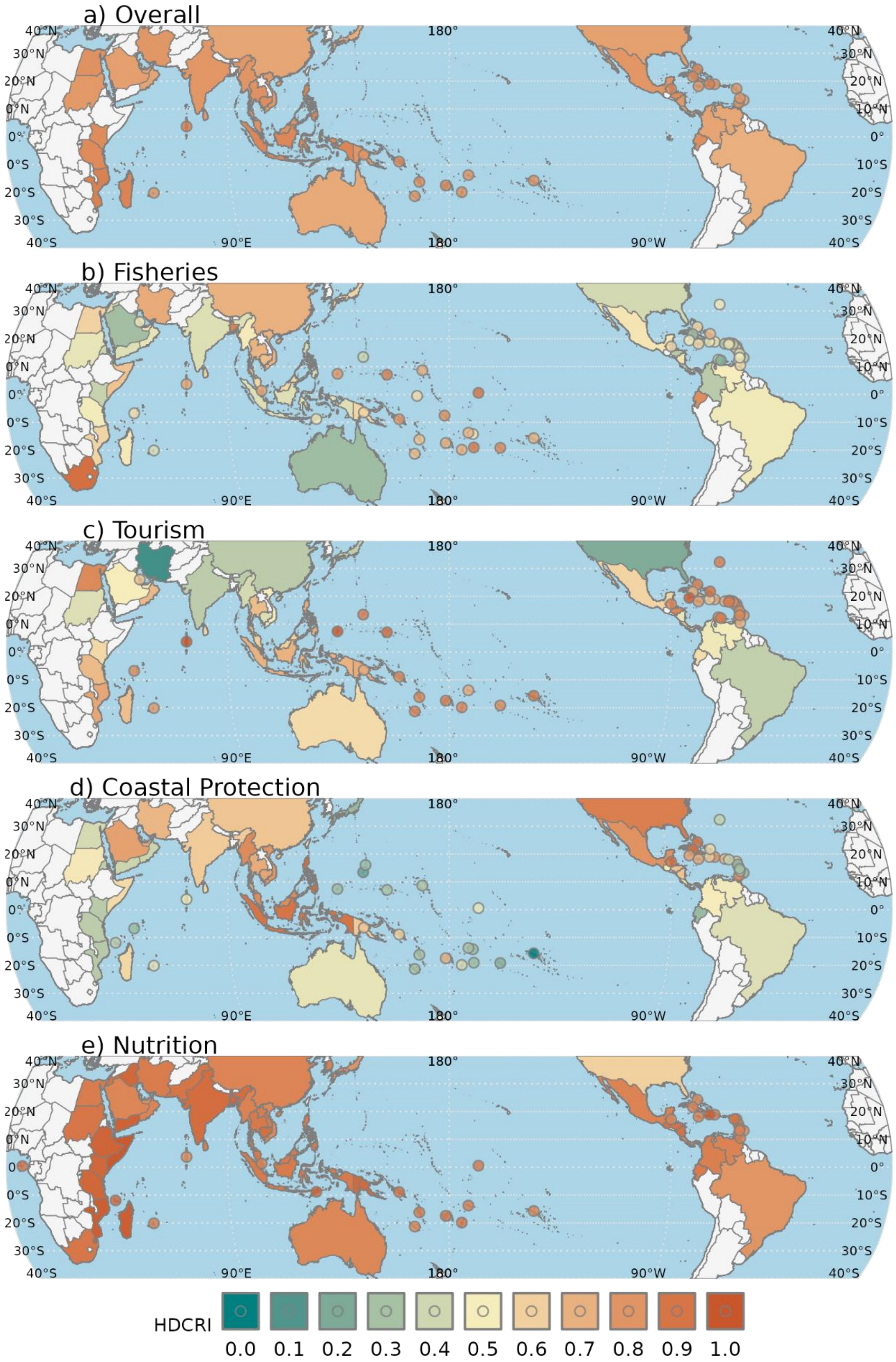

Figure 21. Global map of HDCRI for each category a) overall human dependency b) fisheries, c) tourism, d) coastal protection, and e) nutrition, from a scale of 0 to 1, with 0 representing lowest relative dependency and 1 the highest.

Table 22. Summary of top 10 ranked coral reef countries of HDCRI by dependency categories including total population in 2020 of ranked countries within 50 km and 100 km from coral reefs.

Country Rank	**Overall**	**Fisheries**	**Tourism**	**Coastal Protection**	**Nutrition**
1	Maldives	Wallis and Futuna	Bonaire*	Philippines	Somalia
2	Mozambique	South Africa	Palau	Belize	Mozambique
3	Madagascar	Kiribati	Maldives	Cuba	Madagascar
4	Philippines	Niue	Cayman Islands	Indonesia	Haiti
5	Haiti	Tokelau	Micronesia	The Bahamas	Yemen
6	Belize	Micronesia	British Virgin Islands	United States	Ethiopia
7	Indonesia	Bangladesh	Turks and Caicos	Grenada	Swaziland[†]
8	Grenada	Cook Islands	Guam	Myanmar	Timor-Leste
9	Tanzania	Ecuador	Bermuda	Malaysia	Bangladesh
10	The Bahamas	Israel	Curacao	Mexico	Tanzania
Population on 50 km from coral reefs	280,332,487	681,520	895,465[‡]	296,433,786	44,278,652
Population on 100 km from coral reefs	381,523,139	2,782,347	895,465	413,778,464	66,374,282

*Bonaire population taken from populations of the Caribbean Antilles (ISO3: BES)

† Swaziland population at 50 km from coral reefs is NA

‡ Tourism top 10 countries population in 2020 at 30km = 895,465, at 10km = 895,119 at 5km = 889,426 from coral reefs

Human dependency profiles

Through unsupervised learning techniques such as PPCA, k-means clustering (KC), and hierarchical clustering (HC), we were able to utilise these exploratory analyses to create human dependency profiles. The clustering of principal component scores allowed us to see how similar or dissimilar countries were given the selected indicator data. Following these methods with a linear discriminant analyses using the principal components (LDAPC) from PPCA and clustering groups from KC and HC. We modelled how well they performed in creating human dependency profiles from the original indicator data and how indicators contributed in explaining the variation between groups (Table 23).

Clustered countries can be viewed to have similar profiles and are driven by particular indicators within each human dependency category and are placed into groups based on similarities. However, these groups were found to overlap and therefore for countries that were clustered together across multiple groups the human dependency profile was less defined. Countries that were found on the periphery of the groups were found to be more distinguished in terms of human dependency profiles and the indicator data that influenced them.

Table 23. Summary of LDAPC models and the r-squared values of variables and prediction accuracy of LDAPC models for overall human dependency.

Human dependency category	**Indicators**	**Overall Human Dependency Indicator r^2**		**Within category Indicator r^2**	
		K-means	Hierarchical	K-means	Hierarchical
Fisheries	Pct_mean_reef_val_GDP	0.31	0.26	0.28	0.23
	MeanReef_bio_area_km2	0.01	**0.78***	**0.76***	**0.76***
	Pct_fishermen_100	0.34	0.31	**0.66***	**0.79***
Tourism	pct_reef_spending_tour	**0.66***	**0.79***	**0.68***	**0.87***
	pct_reef_spending_GDP	0.46	0.38	**0.92***	**0.94***
	Pct_reef_tourists	**0.71***	**0.72***	**0.65***	**0.86***
Coastal Protection	A_km2	0.20	0.28	**0.85***	**0.85***
	Annual_averted_damages_GDP	**0.50***	0.30	0.38	0.38
	Pct_pop_LECZ_50	0.39	0.37	**0.53***	**0.53***
Nutrition	MicronutDensityScore_W	**0.56***	**0.62***	**0.56***	**0.54***
	mean_PII	0.01	**0.59***	**0.66***	**0.51***
	Prev_food_insec	0.02	**0.53***	0.38	0.33
	Prev_under_nour	0.03	0.29	**0.67***	**0.66***
Model prediction accuracy (%)		**97.39**	**99.13**		

*indicators with r^2 >0.5

Overall human dependency

The overall human dependency was calculated for countries that had two or more indicators within each human dependency category of fisheries, tourism, coastal protection and nutrition. This indicator data was combined and analysed together to produce results for overall human dependency on coral reef profiles.

PPCA on selected indicator data explained 54% of variation in human dependency on coral reefs based on the first two axes. K-mean clustering methods (KC) generated 3 clusters and hierarchical clustering methods (HC) generated 6 on the principal components for overall human dependency (Figure 22a & b). Overall indicators in the LDAPC-HC trained modelled appeared to explain variation between clusters better than those in the KC model, where r^2 > 0.5 for 6 indicators in HC and only 3 in KC

(Table 23 & Figure 22c &d). In addition, the KC trained model produced a prediction accuracy of 97.39% and HC trained model of 99.13%.

The KC trained model classified 6 countries from cluster 3 to 1 after LDAPC was applied. The HC trained model, classified 6 countries to cluster 1 from the original HC cluster 2. Drawing these countries to cluster 1, where majority of all other coral reef countries were grouped in both KC and HC and did not reveal much in terms of profiling human dependency distinctly. This may suggest that the indicator data for these particular countries wasn't sufficiently distinct for classification once a trained model was applied.

Outliers from KC cluster 1, that are defined in HC as cluster are driven by coastal protection indicators, containing Belize, Cuba, Philippines, and Indonesia. With the potential of annual averted damages to built capital relative to country GDP from flooding ("Annual_averted_damages_GDP") influencing Belize the most, followed by The Bahamas which is defined into cluster 2 (Figure 22a & b). In addition to this, we can see that the United States also within cluster 2 is being driven by the potential area avoided from flooding ("A_km2") in the presence of coral reefs, with Cuba and the Philippines from cluster 1 in HC. The Philippines however, appears to be driven slightly more by the proportion of the population in low elevations coastal zones to within 50 km of coral reefs ("Pct_pop_LECZ_50"), and was ranked 1st in coastal protection dependency using the HDCRI.

Countries with profiles of human dependency on coral reefs within fisheries and tourism were presented in cluster 2 for KC and cluster 3 for HC (Figure 22a & b). Bonaire, Palau and the Maldives, countries which ranked in the top 3 for tourism dependency in the HDCRI, were largely driven by tourism indicators within their cluster.

In particular the proportion of reef to total tourism expenditure by reef visitors (“pct_reef_spending_tour”) and the proportion of reef tourists to all tourists (“Pct_reef_tourists“) which are major contributors in discriminating between clusters with modelled r^2 values of 0.66 and 0.71 respectively for KC and 0.68 and 0.58 respectively for HC (Figure 22c & d).

Human dependency on coral reefs driven by fisheries indicators were found in Kiribati ranked 3rd , Micronesia 6th and Wallis and Futuna 1st for fisheries dependency HDCRI. However, it is notable that only two out of the three fisheries indicators drive this cluster (KC cluster 2 and HC cluster 3), the proportion of coral reef fishermen to the populations within 100 km of coral refs (“Pct_fishermen_100“) and the proportion of mean fisheries values (between 1950 – 2019) to total country GDP (“Pct_mean_reef_val_GDP“).

The mean reef fish biomass to country coral reef area (“MeanReef_bio_area_km2“) was the driver of variation in the opposite direction for cluster 1 for KC, with outlier countries presented as South Africa and Israel which were defined in cluster 4 for HC (Figure 22a & b). Notably, Bangladesh was defined together in cluster 4 in the HC trained model, and the mean reef fish biomass was reported as a significant discriminator between clusters with r^2 = 0.78. These countries appeared closer to countries where nutritional indicators were driving variation.

Within the nutrition human dependency category we provided four indicators compared to all other categories of three. Including two that were not coral reef specific, but are indicators of Sustainability Development Goals 2 for Zero Hunger; these were prevalence of moderate/severe food insecurity in 2020 (“Prev_food_insec”) and prevalence of undernourishment in 2020 (“Prev_under_nour”). Cluster 6 in HC (Figure

22b) presents countries dependent on coral reef for nutrition, and contains Mozambique, Madagascar, Haiti, Somalia and Swaziland all ranked within the top 10 countries for nutritional HDCRI. Where the prevalence of undernourishment was modelled to have a significant contribution to variation between groups with $r^2 = 0.56$ in KC, and of a lower contribution in HC with $r^2 = 0.62$ (Figure 22c & d).

Interestingly, Bangladesh was grouped into cluster 3 for KC and cluster 1 for HC, this may suggest that this country is relying on both the nutritional indicators in group 3 and the mean reef fish biomass to country coral reef area of fisheries as drivers of dependency on coral reefs. Yet, mean reef fish biomass to country coral reef area, has been mapped far from the two other fisheries indicators, and closer to those in nutrition, it could be presumed that this indicator better represents some form of nutritional dependency.

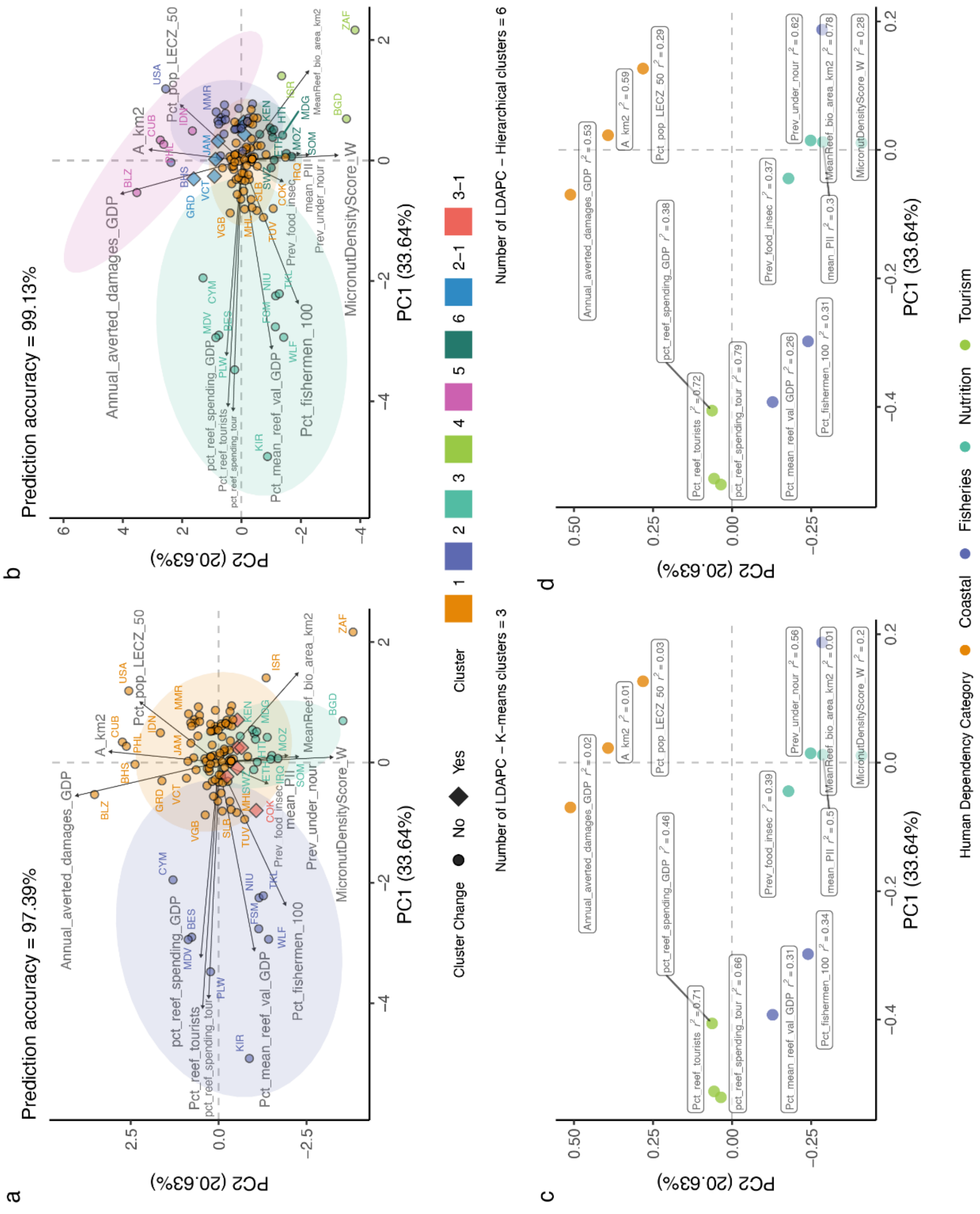

Figure 22. Overall human dependency LDAPC biplots of a) k-means and predicted clusters, b) hierarchical and predicted clusters of coral reef countries PPCA principle components, ellipses represent the 95%CI. Country cluster changes from LDAPC models represented by diamond symbol, and colour presents change where the first number is the initial group obtained from clusters and second number obtained by trained LDAPC models, e.g. 2-3, initially classed in cluster 2 in k-means or hierarchical clustering and classified into cluster 3 by LDAPC model. Indicator variables of PPCA loadings for c) k-means and d) hierarchical LDAPC modelled r^2 coloured by human dependency category. LDAPC model prediction accuracy (%) labelled on top-left of corresponding plots.

Human dependency categories

Overall human dependency calculations classified countries into human dependency profiles based on selected indicators. With hierarchical clustered trained LDAPC models performing better in classifying human dependency profiles than k-mean clustered trained models.

Still many countries are still clustered together in a central space; by applying the hybrid learning methods to all the human dependency categories, we can delve into some of the nuances that may not appear in the overall human dependency results. We are able to identify or highlight more countries with the smaller scale analyses, in addition to understanding how the different clustering methods may affect human dependency profiling.

Fisheries

PPCA on fisheries indicator data ("Pct_mean_reef_val_GDP", "MeanReef_bio_area_km2" and "Pct_fishermen_100") explained 84% of variation in human dependency. This set of variables reflected human dependency on coral reef fisheries by the proportion of mean reef fisheries values (1950 – 2019, Pauly et al., 2020) to country GDP ($USD 2019, International Monetary Fund, 2021; The World Bank, 2022; United Nations, 2021a), mean reef fish biomass (Pauly et al., 2020) to country coral reef area (t/km^2, Sing Wong et al., 2022), and, the proportion of estimated reef fishermen (Teh et al., 2013), to populations within 100 km of coral reefs (Sing Wong et al., 2022), demonstrating economic, reef health thus potential reef fisheries and employment respectively.

Mean reef fish biomass to country coral reef area, best explains the variation for the cluster containing South Africa, Bangladesh and Israel (KC cluster 3 and HC cluster

2), with modelled $r^2 = 0.76$ for both KC and HC (Figure 23c & d). However, HC determined the proportion of reef fishermen to populations within 100 km of coral reefs with $r^2 = 0.79$, as a better descriptor for explaining the variation between groups within this model, and had a prediction accuracy of 99% compared to 98% for KC.

KC cluster 2 and HC cluster 3 represents the outlier countries that are dependent remaining fisheries indicators. However, we can now tease out countries from cluster 1 and observe the directions of which indicators may be driving variation between them the most. For example, we can see that Iran, China, Vietnam and Thailand are driven towards mean reef fish biomass to country coral reef areas, whereas Ecuador, Tuvalu, Palau and Solomon Islands are driven towards the proportion of reef fishermen to populations within 100 km of coral reefs and the proportion of mean reef fisheries value to country GDP (Figure 23a & b).

Notably, we did not see a change of cluster classification in LDAPC KC trained model, but was present in the HC model which has demonstrated a better performance accuracy. This could be signal of Ward's method used in hierarchical cluster, where total within-cluster variance is minimised and tends to produce more compact clusters (Boehmke & Greenwell, 2020).

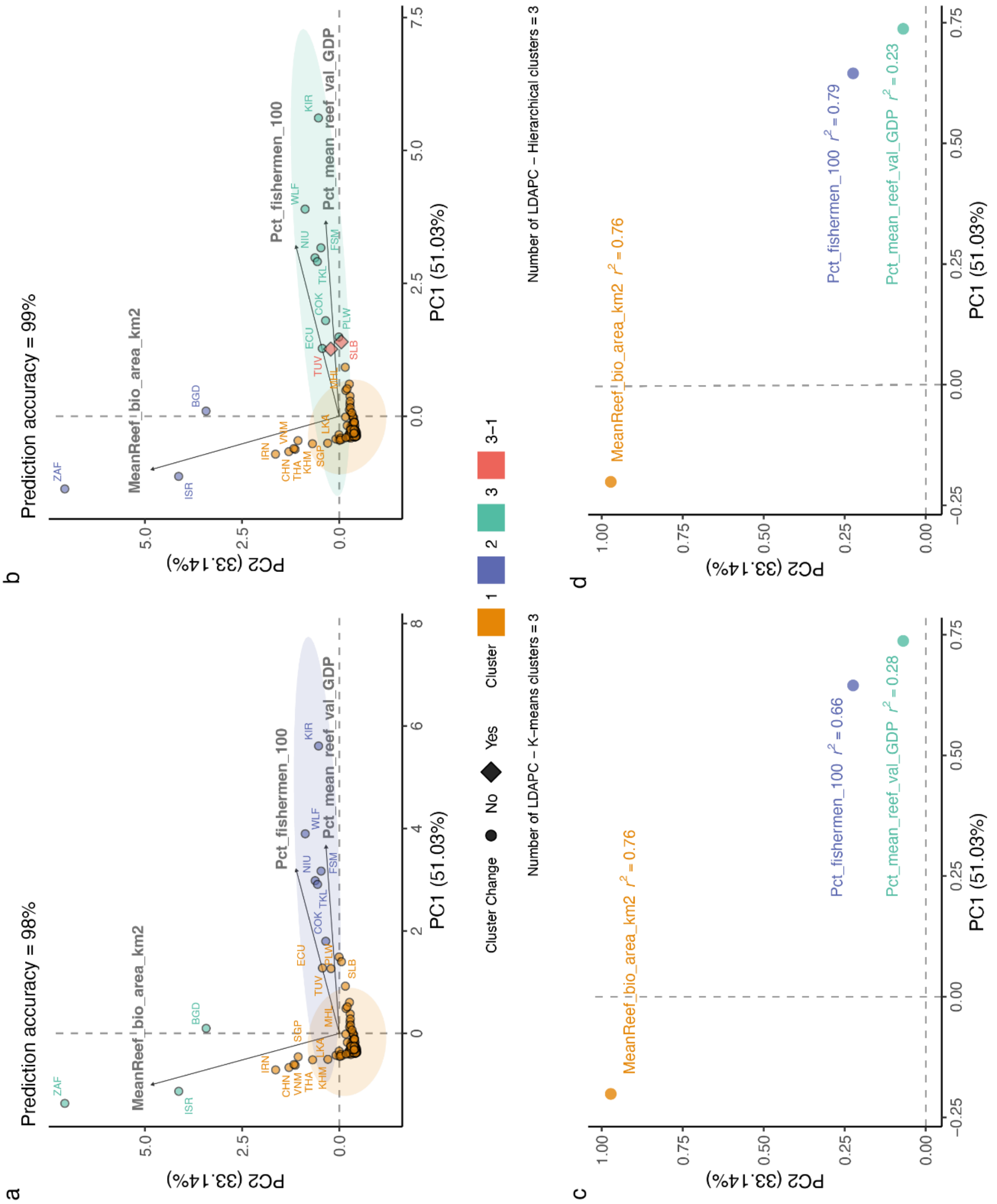

Figure 23. Fisheries human dependency LDAPC biplots of a) k-means and predicted clusters, b) hierarchical and predicted clusters of coral reef countries' PPCA principle components, ellipses represent the 95%CI. Country cluster changes from LDAPC models represented by diamond symbol, and colour presents change where the first number is the initial group obtained from clusters and second number obtained by trained LDAPC models, e.g. 2-3, initially classed in cluster 2 in k-means or hierarchical clustering and classified into cluster 3 by LDAPC model. Indicator variables of PPCA loadings for c) k-means and d) hierarchical LDAPC modelled r^2 coloured by human dependency category. LDAPC model prediction accuracy (%) labelled on top-left of corresponding plots.

Tourism

Tourism PPCA showed that the selected indicator data “pct_reef_spending_GDP”, “Pct_reef_tourists”, and “pct_reef_spending_tour” represented 99.75% of human dependency on coral reef tourism variation based on the first two axes (Figure 24a & b). The selected variables reflected human dependency on coral reef tourism through reef tourism as proportion of GDP, proportion of reef tourists arrival to all tourist arrivals (international and domestic) and, reef visitor expenditure as proportion of total tourism expenditure (Spalding et al., 2017), demonstrating economic, and reputation in terms of popularity in the form of visitors as drivers of tourism dependency on coral reefs.

The optimum number of clusters defined by KC was 3 and HC was 5, with changes in predicted LDAPC groups for both, in KC select countries were moved from cluster 2 to 3 and in HC from cluster 1 to 2, highlighted in Figure 24a & b. How clusters were formed is nicely visualised between Figure 24a & b, and we can observe the differences in cluster formation, where k-means clustering methods used the pre-defined number of optimum clusters of 3 and hierarchical clustering resulted in an optimum of 5 clusters for classifying coral reef countries.

The HC “bottom-up” approach presented cluster 1 containing the majority of coral reef countries, where dependency profiles were not clearly observed, along with cluster 2 similar to that of KC clusters 2 and 3. Yet the remaining 3 clusters in HC were distinct and displayed more clearly which indicators were driving this variation. For example, cluster 3 containing Bonaire and the Cayman Islands, appeared to be driven by the proportion of reef tourists arrivals to all tourists (“Pct_reef_tourists”), suggesting that the overall tourism industry in these countries are reef based. Though, these countries can be observed to be driven slightly towards the reef tourism as proportion of GDP indicator. The final distinct cluster, containing only Micronesia was driven by the reef visitor expenditure as a proportion of total tourism expenditure. However, Micronesia was plotted below the means of this indicator which may suggest that though strongly influenced by reef visitor expenditure, it may be comparatively, lower than other countries.

Both KC and HC grouped the Maldives and Palau into the same cluster and revealed that their dependency profile was driven by the highest values of reef tourism as a proportion of total country GDP ("Pct_reef_spending_GDP"; Figure 24a & b), appearing as major outliers to all other coral reef countries within tourism dependency.

All tourism indicators were found to explain variation well between clusters, with high r^2 values for both KC and HC. Proportion of reef tourism to total country GDP explained the highest proportion of variance between clusters with an r^2 = 0.93 in KC and 0.94 in HC. The prediction accuracy was higher in the KC trained LDAPC model at 9.59% and in the HC trained LDAPC model at 89.74%. However, the proportions of variance explained by the remaining two indicators of proportion of reef tourists to all tourists and proportion of reef visitor expenditure to total tourism expenditure was lower for KC at r^2 = 0.65 and 0.68 respectively, compared to HC r^2 = 0.86 and 0.87 respectively (Figure 24c & d). This implies that the HC trained model, though did not predict the same cluster groupings of countries to that of HC on the PPCA principle components, it does show that the indicators were able to classify clusters better than that of the KC trained model.

Tourism dependency profiles defined by these analyses reveals that all outlier countries located on the right-hand side of the plot, are dependent on tourism for their economy. Where the differences are found is that in the Maldives and Palau tourism is large proportion of their total GDP and in the Cayman Islands, Bonaire, and Micronesia, reef tourism is a large proportion within that sector. Thus, we would presume that higher dependency from tourism on coral reefs is found in the Maldives and Palau. Overall, all these outlier countries show high values of reef tourists to all tourists, indicating that may visitors are there for the coral reefs.

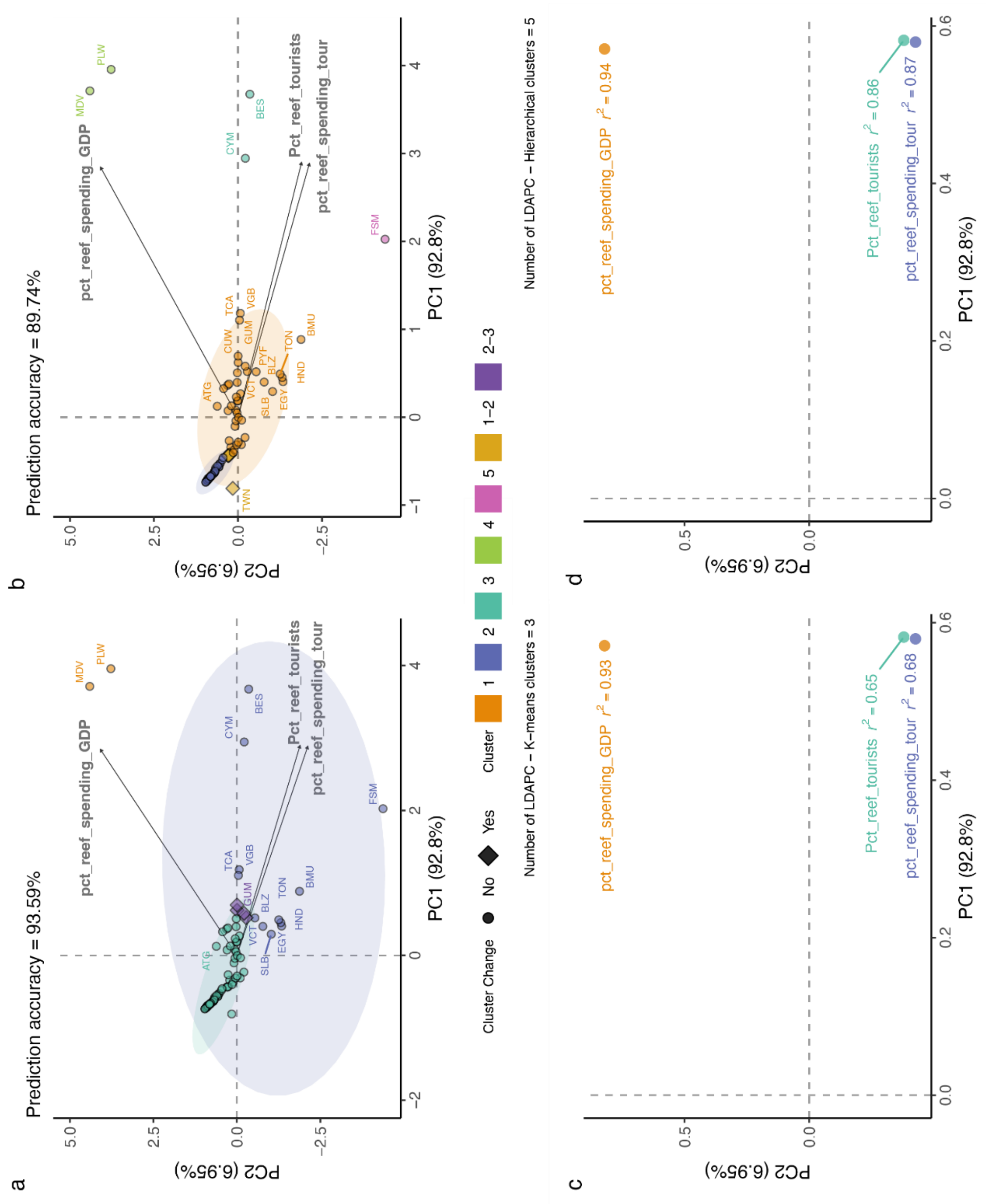

Figure 24. Tourism human dependency LDAPC biplots of a) k-means and predicted clusters, b) hierarchical and predicted clusters of coral reef countries' PPCA principle components, ellipses represent the 95%CI. Country cluster changes from LDAPC models represented by diamond symbol, and colour presents change where the first number is the initial group obtained from clusters and second number obtained by trained LDAPC models, e.g. 2-3, initially classed in cluster 2 in k-means or hierarchical clustering and classified into cluster 3 by LDAPC model. Indicator variables of PPCA loadings for c) k-means and d) hierarchical LDAPC modelled r^2 coloured by human dependency category. LDAPC model prediction accuracy (%) labelled on top-left of corresponding plots.

Coastal Protection

Coastal protection PPCA explained 80% of variation based on the first two axes (Figure 25a & b). These variables characterised human dependency on coastal protection from coral reefs by representing the populations at risk (e.g. the proportion of low elevation coastal zone to 50 km from coral reefs population, “Pct_pop_LECZ_50”), areas protected from potential 100-year event floods by coral reefs (e.g. “A_km2”), and the economic benefits of coral reefs to protect from 100-year event floods (e.g. value of annual expected damages averted to built capital relative to their total GDP, “Annual_averted_damages_GDP”).

Interestingly, both KC and HC trained LDAPC models resulted in 100% prediction accuracy, and both determined optimum number of clusters as 3, grouping countries in the same order (Figure 25a & b). This would suggest that both KC and HC performed well in classification compared to LDAPC, however, with LDAPC we are able to quantify the proportion of variation explained by indicators. The annual area avoided flooded with protection from coral reefs was the best discriminator between clusters where $r^2 = 0.85$ in both KC and HC models, followed by the proportion of LECZ to 50 km from coral reef populations, $r^2 = 0.53$ and finally the annual averted damages to built capital relative to total GDP, $r^2 = 0.38$ for both KC and HC models.

Countries that are driven by areas protected by coral reefs are Indonesia, Philippines , and Cuba; countries which are grouped together in both KC (group 1; Figure 25a) and HC (group 4; Figure 25a). Coastal protection dependency profiles driven by the annual expected damages averted to built capital relative to their total GDP appeared a prominent driver for Belize, which was grouped together with the Bahamas and the United States in cluster 2. Within this cluster however, countries were widely distributed with the Bahamas and particularly the United States also being largely driven by proportion of LECZ populations to populations 50 km from coral reefs.

The biplots for coral reef countries and indicators presents dependency profiles for coastal protection where dependency is present rather countries with and without dependency. Where many of the outlier countries within cluster 1 are radiating towards the influence of indicators, and cluster 2 and 3. This may be due to the nature of the indicator data itself, as this was collected from study which was directly assessing flooding impacts with and without coral reefs. Therefore, all the countries incorporated within this category, would present some level of dependency to coastal protection from coral reefs, what we can observe however, is the countries that may be much more reliant that others.

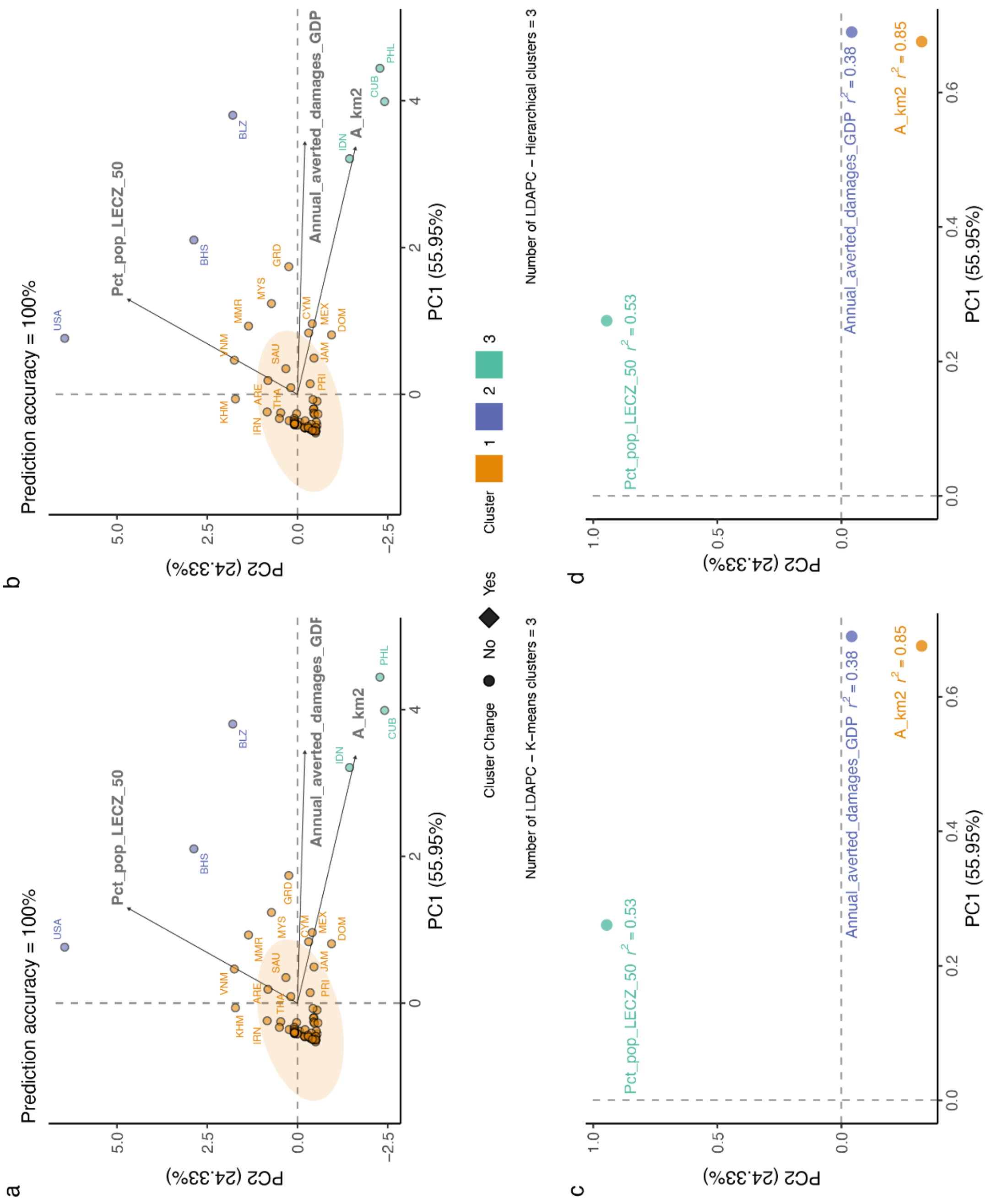

Figure 25. Coastal protection human dependency LDAPC biplots of a) k-means and predicted clusters, b) hierarchical and predicted clusters of coral reef countries' PPCA principle components, ellipses represent the 95%CI. Country cluster changes from LDAPC models represented by diamond symbol, and colour presents change where the first number is the initial group obtained from clusters and second number obtained by trained LDAPC models, e.g. 2-3, initially classed in cluster 2 in k-means or hierarchical clustering and classified into cluster 3 by LDAPC model. Indicator variables of PPCA loadings for c) k-means and d) hierarchical LDAPC modelled r^2 coloured by human dependency category. LDAPC model prediction accuracy (%) labelled on top-left of corresponding plots.

Nutrition

Nutrition PPCA showed that indicators explained 83% of variation based on the first two PCA axes (Figure 26a & b). Nutrition variables described human dependency on nutrition from coral reefs using the micronutrient density availability (%) from coral reef fishes (“MicronutDensityScore_W”), mean prevalence of inadequate intake of 4 key micronutrients (“mean_PII”), the prevalence of moderate/severe food insecurity (%) in 2020 for each country (“Prev_food_insec”) and the prevalence of undernourishment (%) in 2020 for each country (“Prev_under_nour”).

Optimum number of clusters for classification was determined as 4 for both KC and HC. Where LDAPC trained models performed better with the KC model with a prediction accuracy of 98.73% compared to the HC trained model of 89.87%. Clusters were observed to have a large overlaps, however, countries were not so tightly clustered together compared to the PPCA analyses fisheries, tourism and coastal protection dependencies.

The majority of indicators proved to discriminate between clusters well with the prevalence of undernourishment determined as the best with r^2 = 0.67 for KC and 0.66 for HC. Mean prevalence of inadequate intake of 4 key micronutrients r^2 = 0.66 for KC and 0.51 for HC. The micronutrient density availability (%) from coral reef fishes explained r^2 = 0.56 for KC and r^2 = 0.54 for HC of variance between clusters. The indicator which explained the lowest proportion of variance between clusters was prevalence of moderate/severe food insecurity, where r^2 = 0.38 for KC and r^2 =0.33 for HC.

The top 10 countries ranked for nutritional HDCRI can be are observed to the left-hand side of the biplots (Figure 26a & b), where all nutritional indicators are driving towards.

Cluster 3 country outliers of Somalia, Mozambique, Madagascar and Haiti are ranked top 4 in nutrition HDCRI, and we can observe that Somalia and Mozambique are influenced mostly by the mean prevalence of inadequate intake of 4 key micronutrients. However, within the original indicator data “mean_PII” for Somalia, was missing, and was imputed during the PPCA process, for further analysis, hence we must take care with interpretation particularly, with missing data. Nonetheless, Somalia still ranked high in the HDCRI, which excluded missing data points in overall calculations, so we can assume that nutrition is still a major factor for dependency on coral reefs.

As countries are not so tightly clustered and the variance explained by indicators are relatively high and plotted in clear directions, we can begin to produce general nutritional dependency profiles for quadrants in the PPCA biplots. The top-left quadrant describes countries with low micronutrient density availability (%) from coral reef fishes, high mean prevalence of inadequate intake of 4 key micro nutrients (%), high of moderate/severe food insecurity (%) and, high prevalence of undernourishment (%) (Figure 27b). The bottom-right presents the inverse of this, using these descriptors with the indicators we are able to assign risk class to each quadrant, with the top-left quadrant representing countries at high risk on nutritional dependency on coral reefs and the bottom and top-right quadrants representing low risk. The bottom-left quadrant reveals a profile that of high levels of food insecurity, undernourishment, and inadequate intake of key nutrients, however, micronutrient density availability (%) may be high and therefore was assigned medium – high risk (Figure 27c).

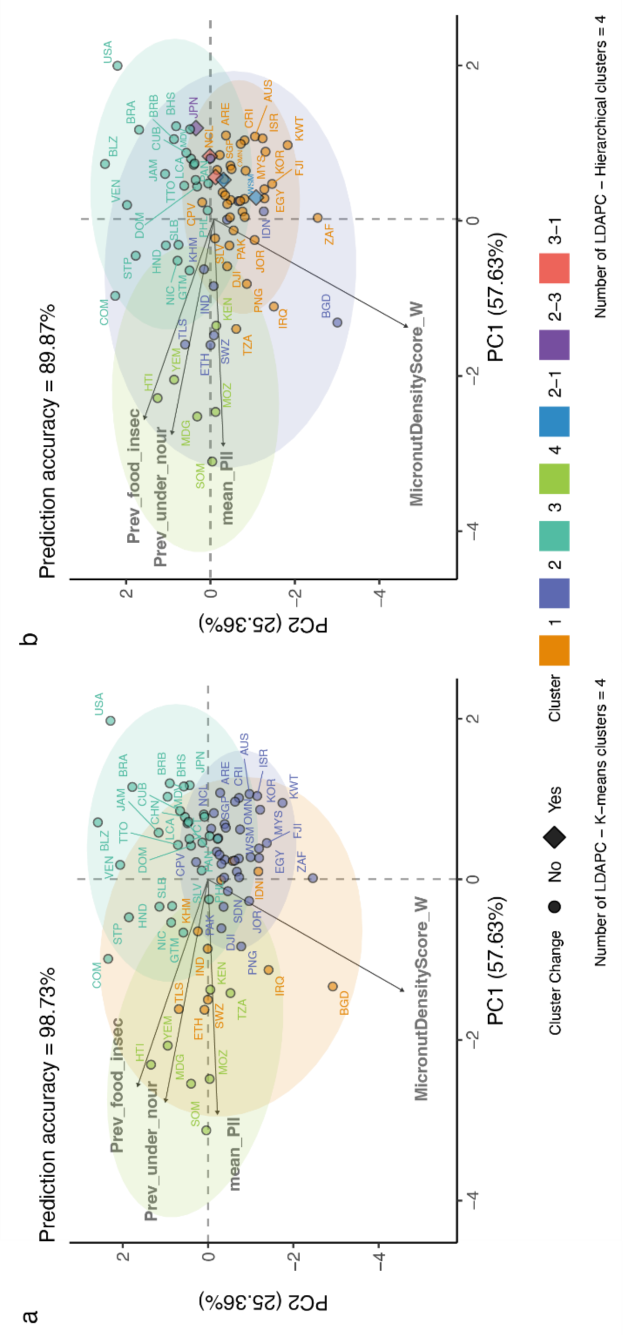

Figure 26. Nutrition human dependency LDAPC biplots of a) k-means and predicted clusters, b) hierarchical and predicted clusters of coral reef countries' PPCA principle components, ellipses represent the 95%CI. Country cluster changes from LDAPC models represented by diamond symbol, and colour presents change where the first number is the initial group obtained from clusters and second number obtained by trained LDAPC models, e.g. 2-3, initially classed in cluster 2 in k-means or hierarchical clustering and classified into cluster 3 by LDAPC model. Indicator variables of PPCA loadings for c) k-means and d) hierarchical LDAPC modelled r^2 coloured by human dependency category. LDAPC model prediction accuracy (%) labelled on top-left of corresponding plots.

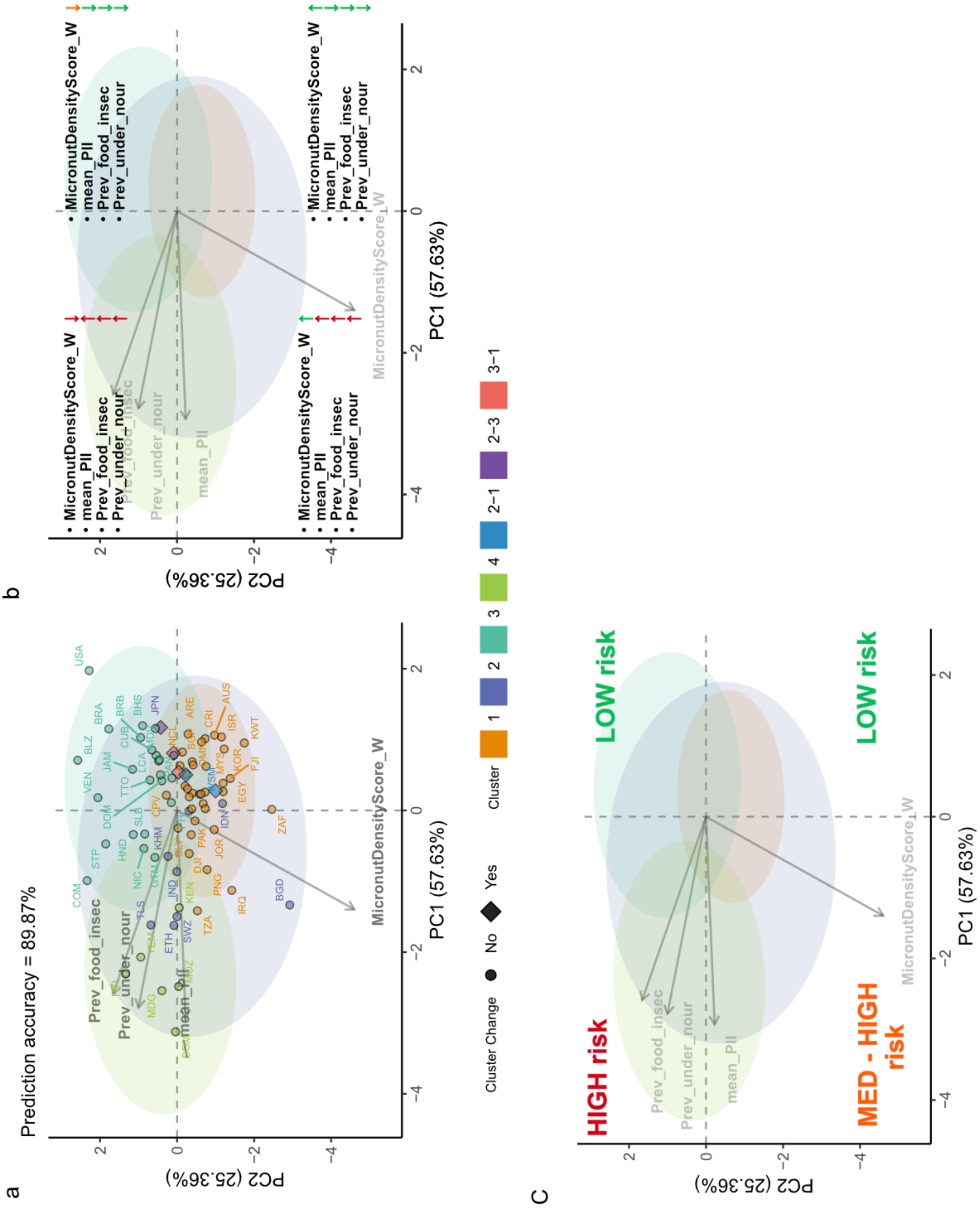

Figure 27. Nutrition human dependency LDAPC biplot of a) hierarchical and predicted clusters of coral reef countries' PPCA principle components, ellipses represent the 95%CI. b) nutritional profiling with indicators of quadrants, arrows present high or low values, colours red = risk, orange = some risk and green = no/low risk, c) quadrant risk level of nutrition human dependency profiles.

Discussion

The human dependency on coral reefs framework we developed enables quantification of fisheries, tourism, nutrition, coastal protection, and subsequently, an “overall” dependency on coral reef ecosystems. The concept of this framework is to provide a baseline from which relative human dependency can be evaluated using global and coral reef specific data. This model will be particularly useful in practical applications such as assessing risk to populations near coral reefs; a tool that can be used by policymakers, risk management for insurance companies, and of course, in coral reef management.

Somewhat of a plug-and-play style, our model is reproducible and allows for continuous updates and improvements, dependent on data availability. To encourage transparency and replicability, we applied our model to global level data that was obtained from open access databases and literature. The framework provides adaptability and was designed to also be used at regional and national levels.

Multiple calculation methods

In order to provide a more holistic view of human dependency and tease out the nuances and complexities of dependency as a whole we investigated multiple methods of summarising human dependency. For a comparative method to other studies, the average of normalised indicator data was calculated to provide a ranked level of dependency that can be compared between coral reef countries. We found that this method, worked well on data that was representative at the country level and avoided using absolute values, that would skew the HDCRI calculations.

However, it must be noted that countries with high nutritional dependencies, may have been due to the SDG indicators included in the calculations and were not specific data representing coral reef explicitly. Nonetheless, it does highlight countries that are vulnerable and could potentially utilise reef fisheries as resource to buffer hunger and access to sufficient nutrients.

We complemented HDCRI analyses with exploratory unsupervised learning techniques that allow the production of “profiles” of human dependency on coral reefs. Through probabilistic principal component analysis and clustering of human dependency indicators, coral reef countries that have similar dependency profiles were identified. It is then possible to see particular drivers within human dependency categories and similarities/dissimilarities between countries. Following with a linear discriminant analysis using clustering groups and principal components from the PPCA, we were able to model how well these countries were classified and perform classification with the primary indicator data collected.

Hierarchical clustering trained linear discriminant model demonstrated better performance in classification of overall human dependency profiles, and provided finer classification of coral reef countries. We found that generally more with more discrete clusters, allowed for easier interpretation of overall human dependency profiles on coral reefs. However, K-means and hierarchical clustering methods both demonstrated varying levels of prediction accuracy when applied to LDAPC modelling of fisheries, tourism, coastal protection and nutrition dependency categories.

The LDAPC trained models, not only enhances classification of human dependency profiles for coral reef countries it allowed us to quantify the drivers of the differences/change in the profiles. Thus, facilitate in identifying indicators or categories of human dependency on coral reefs that may be critical to particular countries.

As hybrid learning methods, can generally be computational heavy, we have presented two clustering methods for analysing human dependency. Where k-means clustering is a popular method as they are suited to large datasets and normally less computationally intensive. K-values can be difficult to predict, and though we can automate through cross-validation algorithms to achieve this. Adjustments of k-values to suit data structure and type may be improved with the assistance of manual adjustments. This is where hierarchical clustering is favourable, however, for large datasets could prove slow computationally and possible expensive.

We hope using multiple but complementary methods, supports a shift from thinking about human dependency in a linear fashion of relative rankings from high to low, towards examining them more specifically i.e. “How coral reef countries are dependent on the ecosystem?”. We believe the hybrid learning approach begins to disentangle the nuances of the multifaceted factors that influence human dependency on coral reefs.

Human dependency profiling

In overall HDCRI analyses, we also lose up to half of the countries compared to when considering fisheries dependency alone due to the high number of data gaps. In conjunction with the hybrid learning methods we are able to define quite general profiles of overall human dependency on coral reefs. Nevertheless, when evaluating countries on the “extremes” of the analyses we are able to determine some of the main drivers of human dependency on coral reefs for the countries within the analysis.

Overall human dependency

We demonstrate that using hierarchical clustering methods for overall human dependency analysis within hybrid learning methods, classification accuracy is better and produces more distinctive clusters. For example, within HC trained models cluster 6 was a distinct group that was driven by nutritional indicators and was not distinguished with KC methods.

Overall human dependency with hybrid learning methods, does still struggle to create distinctive groups for accurate dependency profiling. However, it provides a good baseline for which to begin to investigate dependency profiles at the category level. Across human dependency categories, we were able to tease out the nuances of human dependency on coral reefs, and observe what is driving particular differences between and within groups.

Fisheries

Fisheries profiles revealed that the mean reef fish biomass to country coral reef area was driving variation differently to that of proportion of coral reef fishermen to coral reef population at 100 km and proportion of mean reef fisheries value to country total GDP.

We were able to distinguish countries that are currently dependent on reef fisheries for their economy and employment. For example, Kiribati was shown to have a high proportion of mean reef fisheries value to country total GDP, which is expected of a small Pacific island nation and is classified as a small island developing state (SID, UN-OHRLLS, 2017). Kiribati households participate primarily in agriculture and fishing where it has been reported that 58% of households rely solely on these two forms of income (Reddy et al., 2014). Wallis and Futuna, presents high proportion of fishermen to populations with 100 km from coral reefs, thus dependent on fisheries for employment. Which we would expect again from a small Pacific island nation, where around a third of the populations practise small-scale fisheries using nets and spearguns (Hamel et al., 2013). It is noted that the coral reef population derived for Wallis and Futuna, is likely to fall within much closer distances that 100 km.

Mean reef fish biomass to country coral reef area, represents dependency as the reef health thus potential reef fisheries. In which South Africa was highly driven by this indicator and suggests that coral reef health is a driver for dependency. As observed in the overall human dependency analysis, mean reef fish biomass was plotted towards nutritional indicators and may actually be more indicative of nutritional dependency.

Tourism

Within tourism dependency we demonstrate how we can begin to describe dependency profiles. Hybrid analysis was able to classify countries that were highly dependent on coral reefs, but at different scales. Where we revealed that tourism can drive the economy within the tourism sector (Cayman Islands and Bonaire) and for the entire country as was for the Maldives and Palau.

Tourism contributes to nearly a third of the GDP in the Maldives, and is highly dependent on this sector (World Bank, 2022). It has faced great shocks with the COVID-19 pandemic and outbreak of war in Ukraine, where the heavily-import dependent country faces shocks due to rises in global commodities. Though, tourism has now recovered to near pre-pandemic levels we are able to identify the levels at which tourism dependency from coral reefs works within a country and how dependency can turn into potential risk.

Coastal Protection

Coastal protection hybrid analysis, presents data which was specifically designed to assess global flood protection i.e. coastal protection provided by coral reefs (Beck et al., 2018). Here we do not consider the profile to be that of countries that do and do not rely on coastal protection, rather than what is the main influence for coastal protection to coral reef countries. Where the Philippines, Cuba and Indonesia, were driven by greater values for land areas protected by coral reefs from flooding, in addition to the economic benefits of coral reefs to protect from 100-year event floods. A recent study by Burke & Spalding (2022) assessing shoreline protection by coral reefs across the globe identified many of the same countries in that had the largest coral reef areas to those of our analysis.

Nutrition

The nutrition dependency category consisted of indicators designed to be coral reef specific with global indicators of hunger from Sustainable Development Goals. Here the mix of indicators presented countries that were of varying scales of dependency to low or even no dependency on coral reefs for nutrition. Due to this variation, countries were distributed more evenly, than other dependency categories, and indicators was driving variation to one side of the biplots.

This created an opportunity to develop human dependency profiles across all four quadrants of the biplots, using the hierarchical clustering method as the example. We could define how indicators were presenting in countries, depending on the location in the biplots, the two right-hand side quadrants presenting low hunger and food insecurity with either high or low micronutrient availability. On the other side, we defined the quadrants as high risk, these countries presented high values for hunger, food insecurity and low values for micronutrient density availability from coral reef fish. The final quadrant was assigned as medium to high risk where hunger and food insecurity was high, how micronutrient availability was also higher. Therefore, we assumed that these countries have the opportunity to use coral reefs as a resource against nutritional deficiencies. This type of risk profiling will prove useful in policy and even to facilitate underwriting of insurance policies to protect coral reefs and the populations that rely on them.

Conclusion

Our study encourages a change in thinking about human dependency on coral reefs. Using methods to simply quantify human dependency in a linear manner such as HDCRI provides a one-dimensional view of human dependency. We have demonstrated that applying multiple methods to model human dependency provides a more holistic view of dependency and complementing analyses with hybrid learning methods can facilitate shifts in human dependency concepts.

Using novel methods for calculating human dependency has allowed for further understanding of how human dependency on coral reefs is similar and differs between countries and the factors that are driving dependency. It must be noted that our results are tuned to the resolution of the data used within the model analyses, therefore, with greater detail in data and more indicators of human dependency, models will improve, allowing more representative quantitative indices of human dependency in the future using the framework provided here.

We believe our models, and future improvements in data supplied to such models, will facilitate international policies such as UN Sustainable Development Goals (United Nations, 2021b), and allow for more informed coral reef management by incorporating further human aspects, where ecosystems funds in marine conservation are unevenly distributed (McClanahan, 2020). Focusing finance and support to coral reef communities is crucial - our models are another tool to help target such financing. Additionally, we hope the models can be applied as novel methods for risk assessments within insurance and reinsurance companies, facilitating underwriting of the parametric insurance policies (World Bank, 2019) that have begun insuring our natural ecosystems, supporting the people that depend on them.

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Appendix

Material and methods

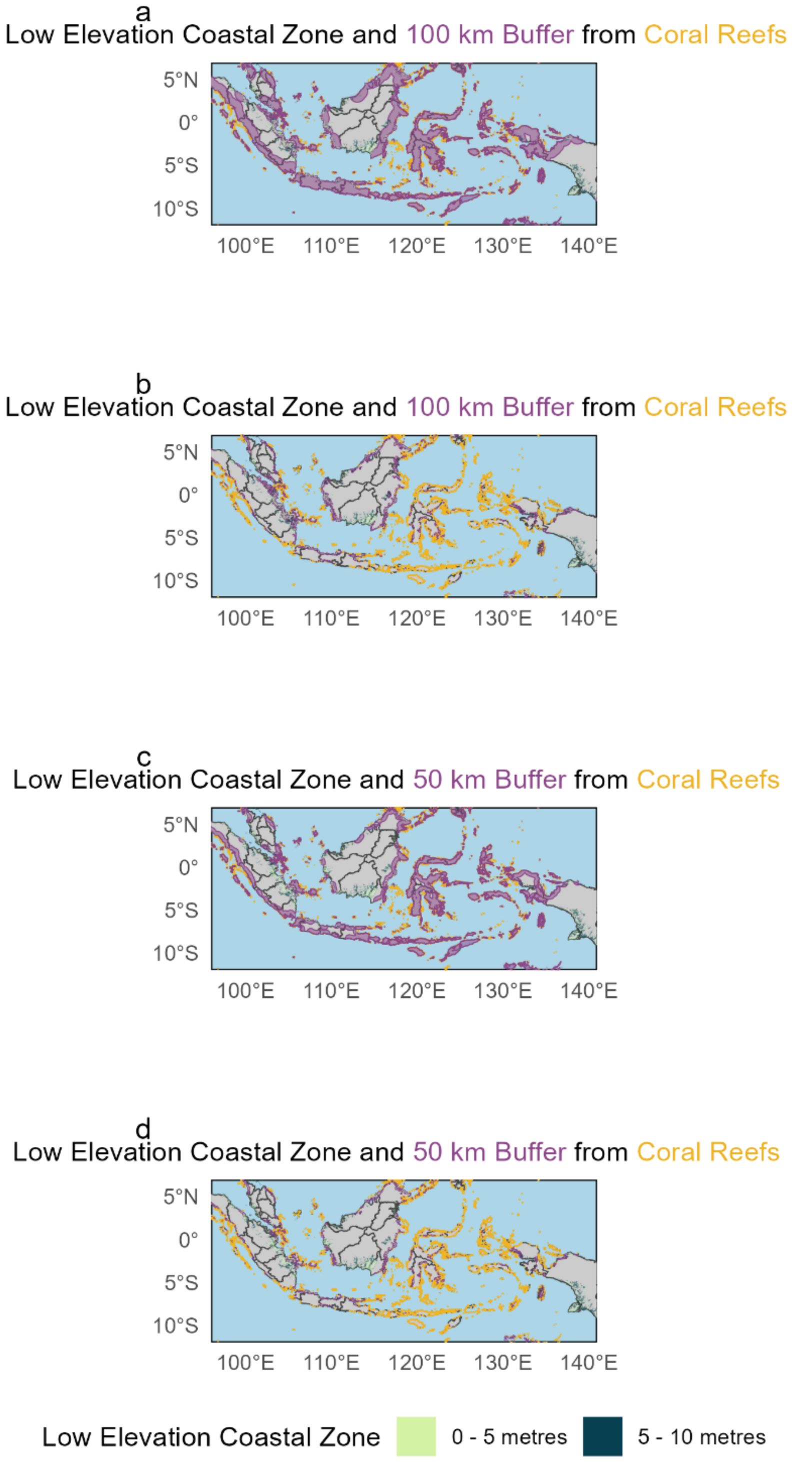

Figure S28. Maps of Southeast Asia low elevation coastal zones, overlaid with buffers at a) 100 km and c) 50 km from coral reefs and the intersections of LECZ and buffers at b) 100 km and d) 50 km.

Table S24. Summary of countries included in HDCRI calculations within human dependency categories and the number of indicators used in calculations.

ISO3	Country	Fisheries	Tourism	Coastal Protection	Nutrition	Overall
ABW	Aruba	3	2	-	-	-
AIA	Anguilla	3	2	-	-	-
ARE	United Arab Emirates	3	3	3	4	13
ASM	American Samoa	3	-	2	-	-
ATG	Antigua and Barbuda	3	3	3	3	12
AUS	Australia	3	3	3	3	12
BES	Bonaire	2	2	-	-	-
BGD	Bangladesh	3	-	-	4	-
BHR	Bahrain	3	3	-	-	-
BHS	The Bahamas	3	3	3	3	12
BLZ	Belize	3	3	3	4	13
BMU	Bermuda	3	3	2	-	-
BRA	Brazil	3	3	3	4	13
BRB	Barbados	3	3	2	4	12
BRN	Brunei Darussalam	3	3	3	3	12
CHN	China	3	3	3	2	11
COK	Cook Islands	3	2	2	-	-
COL	Colombia	3	3	3	3	12
CRI	Costa Rica	3	3	3	4	13
CUB	Cuba	3	3	3	2	11
CUW	Curacao	2	2	-	-	-
CYM	Cayman Islands	3	2	3	-	-
DJI	Djibouti	3	-	3	4	-
DMA	Dominica	3	-	2	2	-
DOM	Dominican Republic	3	3	3	3	12
ECU	Ecuador	3	3	2	4	12
EGY	Egypt	3	3	3	4	13
ERI	Eritrea	3	-	3	-	-
FJI	Fiji	3	3	3	4	13
FSM	Micronesia	3	3	2	-	-
GLP	Guadeloupe	2	2	3	-	-
GRD	Grenada	3	2	2	3	10
GUM	Guam	3	2	2	-	-
HND	Honduras	3	3	3	4	13
HTI	Haiti	3	3	3	4	13
IDN	Indonesia	3	3	3	4	13
IND	India	3	3	3	3	12
IRN	Iran	3	3	3	4	13
ISR	Israel	3	-	-	3	-
JAM	Jamaica	3	3	3	4	13
JOR	Jordan	3	-	-	4	-

JPN	Japan	3	3	2	4	12
KEN	Kenya	3	3	3	4	13
KHM	Cambodia	3	3	3	4	13
KIR	Kiribati	3	-	3	4	-
KNA	Saint Kitts and Nevis	3	3	-	2	-
KWT	Kuwait	3	3	3	4	13
LCA	Saint Lucia	3	3	2	2	10
LKA	Sri Lanka	3	3	3	4	13
MDG	Madagascar	3	3	3	4	13
MDV	Maldives	3	3	3	3	12
MEX	Mexico	3	3	3	4	13
MHL	Marshall Islands	2	-	3	-	-
MMR	Myanmar	3	3	3	4	13
MOZ	Mozambique	3	3	3	4	13
MSR	Montserrat	2	-	-	-	-
MTQ	Martinique	2	2	3	-	-
MUS	Mauritius	3	3	2	4	12
MYS	Malaysia	3	3	3	3	12
MYT	Mayotte	2	-	2	-	-
NCL	New Caledonia	3	2	3	3	11
NIC	Nicaragua	3	3	3	3	12
NIU	Niue	2	-	2	-	-
NRU	Nauru	3	-	-	-	-
OMN	Oman	3	3	3	3	12
PAN	Panama	3	3	3	3	12
PHL	Philippines	3	3	3	4	13
PLW	Palau	3	3	2	-	-
PNG	Papua New Guinea	3	3	3	2	11
PRI	Puerto Rico	3	3	3	-	-
PYF	French Polynesia	3	2	3	3	11
QAT	Qatar	3	3	3	-	-
REU	Reunion	2	-	2	-	-
SAU	Saudi Arabia	3	3	3	3	12
SDN	Sudan	3	3	3	4	13
SGP	Singapore	2	-	-	2	-
SLB	Solomon Islands	3	3	3	3	12
SOM	Somalia	3	-	3	3	-
SXM	Sint Maarten	2	2	-	-	-
SYC	Seychelles	3	3	2	-	-
TCA	Turks and Caicos	3	2	3	-	-
THA	Thailand	3	3	3	4	13
TKL	Tokelau	2	-	-	-	-
TLS	Timor-Leste	3	-	-	3	-
TON	Tonga	3	3	3	2	11
TTO	Trinidad and Tobago	3	3	-	4	-
TUV	Tuvalu	3	-	-	-	-
TWN	Taiwan	3	2	3	-	-
TZA	Tanzania	3	3	3	4	13

USA	United States	2	3	3	3	11
VCT	Saint Vincent and the Grenadines	3	3	-	4	-
VEN	Venezuela	3	3	3	3	12
VGB	British Virgin Islands	3	2	-	-	-
VIR	US Virgin Islands	3	2	2	-	-
VNM	Vietnam	3	3	3	4	13
VUT	Vanuatu	3	3	3	4	13
WLF	Wallis and Futuna	2	-	2	-	-
WSM	Samoa	3	3	2	4	12
YEM	Yemen	3	-	3	3	-
ZAF	South Africa	2	-	-	4	-
COM	Comoros	-	-	2	2	-
CPV	Cabo Verde	-	-	-	3	-
ETH	Ethiopia	-	-	-	3	-
GTM	Guatemala	-	-	3	4	-
IRQ	Iraq	-	-	-	3	-
KOR	South Korea	-	-	-	3	-
LAO	Loas	-	-	-	3	-
PAK	Pakistan	-	-	-	4	-
STP	Sao Tome and Principe	-	-	-	4	-
SWZ	Swaziland	-	-	-	3	-
SLV	El Salvador	-	-	-	4	-
IOT	Chagos	-	-	2	-	-
MNP	Northern Mariana Islands	-	-	2	-	-
PCN	Pitcairn Islands	-	-	2	-	-
UMI	Baker Island	-	-	2	-	-

Table S25. Detailed summary of LDAPC models with k-means and hierarchical clustered PPCA across human dependency categories.

Category	**Model Code**	**Formula**	**Indicators**	**Indicator r^2**	**Model prediction accuracy (%)**
Overall	LDAPC-K	*LDA(formula = K_cluster ~ Overall_ind_pca_PC1 + Overall_ind_pca_PC2, data = lda_df_K_PC, missing = 'Imputation (replace missing values with estimates)')*			*94.78*
		LDA(formula = K_cluster ~ Pct_mean_reef_val_GDP + MeanReef_bio_area_km2 + Pct_fishermen_100 + pct_reef_spending_tour + pct_reef_spending_GDP + Pct_reef_tourists + MicronutDensityScore_W + mean_PII + Prev_food_insec + Prev_under_nour + A_km2 + Annual_averted_damages_GDP + Pct_pop_LECZ_50, data = lda_df_K_ind, missing = 'Imputation (replace missing values with estimates)'	Pct_mean_reef_val_GDP	0.31	**97.39**
			MeanReef_bio_area_km2	0.01	
			Pct_fishermen_100	0.34	
			pct_reef_spending_tour	**0.66**	
			pct_reef_spending_GDP	0.46	
			Pct_reef_tourists	**0.71**	
			MicronutDensityScore_W	0.20	
			mean_PII	**0.50**	
			Prev_food_insec	0.39	
			Prev_under_nour	**0.56**	
			A_km2	0.01	
			Annual_averted_damages_GDP	0.02	
			Pct_pop_LECZ_50	0.03	
	LDAPC-Hier	*LDA(formula = hier_cluster ~ Overall_ind_pca_PC1 + Overall_ind_pca_PC2, data = lda_df_hier_PC, missing = 'Imputation (replace missing values with estimates)')*			94.78
		LDA(formula = hier_cluster ~ Pct_mean_reef_val_GDP + MeanReef_bio_area_km2 + Pct_fishermen_100 + pct_reef_spending_tour + pct_reef_spending_GDP + Pct_reef_tourists + MicronutDensityScore_W + mean_PII + Prev_food_insec + Prev_under_nour + A_km2 + Annual_averted_damages_GDP + Pct_pop_LECZ_50, data = lda_df_hier_ind, missing = 'Imputation (replace missing values with estimates)')	Pct_mean_reef_val_GDP	0.26	**99.13**
			MeanReef_bio_area_km2	**0.78**	
			Pct_fishermen_100	0.31	
			pct_reef_spending_tour	**0.79**	
			pct_reef_spending_GDP	0.38	
			Pct_reef_tourists	**0.72**	
			MicronutDensityScore_W	0.28	
			mean_PII	0.30	
			Prev_food_insec	0.37	
			Prev_under_nour	**0.62**	
			A_km2	**0.59**	
			Annual_averted_damages_GDP	**0.53**	
			Pct_pop_LECZ_50	0.29	
Fisheries	LDAPC-K	LDA(formula = K_cluster ~ Fish_ind_pca_PC1 + Fish_ind_pca_PC2, data = lda_df_K_PC, missing = 'Imputation (replace missing values with estimates)')			100.00

		LDA(formula = K_cluster ~ Pct_mean_reef_val_GDP + MeanReef_bio_area_km2 + Pct_fishermen_100, data = lda_df_K_ind, missing = 'Imputation (replace missing values with estimates)')	Pct_mean_reef_val_GDP MeanReef_bio_area_km2 Pct_fishermen_100	0.28 **0.76** **0.66**	**98.00**
	LDAP C-Hier	*LDA(formula = hier_cluster ~ Fish_ind_pca_PC1 + Fish_ind_pca_PC2, data = lda_df_hier_PC, missing = 'Imputation (replace missing values with estimates)')*			98.00
		LDA(formula = hier_cluster ~ Pct_mean_reef_val_GDP + MeanReef_bio_area_km2 + Pct_fishermen_100, data = lda_df_hier_ind, missing = 'Imputation (replace missing values with estimates)')	Pct_mean_reef_val_GDP MeanReef_bio_area_km2 Pct_fishermen_100	0.23 **0.76** **0.79**	**99.00**
Tourism	LDAP C-K	*LDA(formula = K_cluster ~ Tour_ind_pca_PC1 + Tour_ind_pca_PC2, data = lda_df_K_PC, missing = 'Imputation (replace missing values with estimates)')*			94.87
		LDA(formula = K_cluster ~ pct_reef_spending_tour + pct_reef_spending_GDP + Pct_reef_tourists, data = lda_df_K_ind, missing = 'Imputation (replace missing values with estimates)')	pct_reef_spending_tour pct_reef_spending_GDP Pct_reef_tourists	**0.68** **0.92** **0.65**	**93.59**
	LDAP C-Hier	*LDA(formula = hier_cluster ~ Tour_ind_pca_PC1 + Tour_ind_pca_PC2, data = lda_df_hier_PC, missing = 'Imputation (replace missing values with estimates)')*			94.87
		LDA(formula = hier_cluster ~ pct_reef_spending_tour + pct_reef_spending_GDP + Pct_reef_tourists, data = lda_df_hier_ind, missing = 'Imputation (replace missing values with estimates)')	pct_reef_spending_tour pct_reef_spending_GDP Pct_reef_tourists	**0.87** **0.94** **0.86**	**89.74**
Coastal Protection	LDAP C-K	*LDA(formula = K_cluster ~ Coast_ind_pca_PC1 + Coast_ind_pca_PC2, data = lda_df_K_PC, missing = 'Imputation (replace missing values with estimates)')*			100.00
		LDA(formula = K_cluster ~ A_km2 + Annual_averted_damages_GDP + Pct_pop_LECZ_50 , data = lda_df_K_Ind, missing = 'Imputation (replace missing values with estimates)')	A_km2 Annual_averted_damages_GDP Pct_pop_LECZ_50	**0.85** 0.38 **0.53**	**100.00**
	LDAP C-Hier	*LDA(formula = hier_cluster ~ Coast_ind_pca_PC1 + Coast_ind_pca_PC2, data = lda_df_hier_PC, missing = 'Imputation (replace missing values with estimates)')*			100.00
			A_km2	**0.85**	**100.00**

		LDA(formula = hier_cluster ~ A_km2 + Annual_averted_damages_GDP + Pct_pop_LECZ_50 , data = lda_df_hier_Ind, missing = 'Imputation (replace missing values with estimates)')	Annual_averted_damages_GDP	0.38	
			Pct_pop_LECZ_50	**0.53**	
Nutrition	LDAP C-K	*LDA(formula = K_cluster ~ Nutr_ind_pca_PC1 + Nutr_ind_pca_PC2, data = lda_df_K_PC, missing = 'Imputation (replace missing values with estimates)')*			100.00
		LDA(formula = K_cluster ~ MicronutDensityScore_W + mean_PII + Prev_food_insec + Prev_under_nour, data = lda_df_K_ind, missing = 'Imputation (replace missing values with estimates)')	MicronutDensityScore_W	**0.56**	**98.73**
			mean_PII	**0.66**	
			Prev_food_insec	0.38	
			Prev_under_nour	**0.67**	
	LDAP C-Hier	*LDA(formula = hier_cluster ~ Nutr_ind_pca_PC1 + Nutr_ind_pca_PC2, data = lda_df_hier_PC, missing = 'Imputation (replace missing values with estimates)')*			93.67
		LDA(formula = hier_cluster ~ MicronutDensityScore_W + mean_PII + Prev_food_insec + Prev_under_nour, data = lda_df_hier_ind, missing = 'Imputation (replace missing values with estimates)')	MicronutDensityScore_W	**0.54**	**89.87**
			mean_PII	**0.51**	
			Prev_food_insec	0.33	
			Prev_under_nour	**0.66**	

Chapter 4: Thesis Summary

Introduction

This chapter will conclude the overall studies by summarising the key research findings in relation to the research aims and questions. I will discuss the value and contribution of the research to the wider community and field, review the limitations of the studies and the potential opportunities for future research.

I will review the findings of populations near coral reefs over time and space and how this is often used as a proxy for dependency, and conversely, threats to coral reefs ecosystems. Finally, I will review human dependency on coral reefs when modelling data from openly accessible data.

Overall findings

I found that in 2020 nearly a billion people lived with 100 km of coral reefs across 117 coral reef countries (Chapter 2: An assessment of people living by coral reefs over space and time, Sing Wong et al. 2022). This is double the highly quoted statistic of 500 million people whom rely on coral reefs (C. Wilkinson, 2004b). Coral reef population density was 4 times higher between 5 to 10 km from coral reefs compared to the global average and generic coastal population trends (Barbier, 2014b; Neumann et al., 2015b). Further findings show that human populations near coral reefs have population growth higher than that of the global average. For example, in The Middle East the average population growth rate was above 3%, due to economic diversification away from oil towards tourism leading to coastal megadevelopments (Burt & Bartholomew, 2019b).

Nearly half of the populations in the Pacific live within 10 km of coral reefs (47.17%), and up to 94% of Small Island Developing States live within 100km of coral reefs. Additionally, there are 60 coral reef countries that have 100% of their population within 100 km of coral reefs. Including Kiribati, Nauru, American Samoa and Niue to name a few that had 100% of their populations within 5 km of coral reefs which matched a study by Andrew et al. (2019).

Chapter 2, firstly aimed to compile a comprehensive list of global coral reef countries; this was achieved through coral reef distribution maps and literature. Secondly, I aimed to update the statistics of human populations near coral reefs; my analyses resulted in a global long-term dataset covering a 20-year period from 2000 to 2020. This baseline assessment will allow coral scientists, managers, and policymakers to understand the temporal changes of human populations near coral reefs. Overall, this will contribute to intentional decision-making, where funds and resources can be allocated accordingly. Which is crucial to achieving the UN Sustainability Development Goals (SDGs), in particular addressing SDG 14 Life Below Water, which highlights that a mere 1.2% of national research budgets are allocated to ocean sciences – our data also helps bridge the country-level data gap for addressing SDG 13 on Climate Action (Guterres, 2020). This country-level data will also allow governments and donors to efficiently quantify populations at risk, allocate financial resources, plan interventions (Palacios-Lopez et al., 2019b), and formulate mitigation strategies against extreme climatic events.

Chapter 3, aimed to redirect the thinking and methodology applied to calculating human dependency on coral reefs through developing a conceptual framework for human dependency. I developed a conceptual framework that was designed to be adaptable to new data and applied at different scales (e.g. global, regional and national levels). The framework was based on an indicator approach, where data was defined from literature into four categories of human dependency on coral reefs: fisheries, tourism, coastal protection, nutrition, and the overall dependency combined all data within these categories.

Using an adapted methodology from Pendleton et al. (2016) I created a human dependency on coral reef index (HDCRI) which took the average of normalised indicator data to calculate HDCRI. The complementary hybrid learning techniques of probabilistic principal component analyses with k-means and hierarchical clusters, followed by linear discriminant analyses on principle components facilitated the creation of a more holistic perspective of human dependency on coral reefs, through human dependency "profiles". These dependency profiles presented how each coral reef country was dependent on coral reefs, not just the usual linear thinking of low to high dependency; and which indicators influenced dependency the most. I demonstrated that using an indicator approach with hybrid learning methods, varying types of dependency profiles can be created Where assessment of dependency may be revealed along a gradient of economic benefits, to creating a risk matrix from coral reef related data and generalised global data.

Contribution to the field

An assessment of people living by coral reefs over space and time (Chapter 2) has provided the first long term dataset of human populations near coral reefs over a 20-year time period from 2000 to 2020. This has resulted in a *Global Change Biology* publication (Chapter 2; https://onlinelibrary.wiley.com/doi/10.1111/gcb.16391). The dataset and baseline assessment of human populations near coral reefs has created accessibility to global temporal data that has often been overlooked. Within coral research human population statistics have been recycled over and over, with few studies that have updated these statistics. In particular, we have provided country-level data which can be applied to policy and frameworks such as the UN Sustainability Development Goals. This scale of data analysis can also be applied to novel methods in climate mitigation and adaptation plans, such as insurance, where the population statistics, can facilitate in risk assessments on coral reefs. Additionally, the methodology used to extract human populations can be applied to regional or national level data which can reveal finer resolutions of populations near coral reefs, and further applied to regional and/or national level policies, management and research.

My final study (Chapter 3), built upon the human dependency methodology from Pendleton et al. (2016), and complemented human dependency index scores with hybrid learning techniques to create dependency “profiles”. I developed a conceptual human dependency framework where the methodology can be reproduced with the aim to bring more standardisation to the calculation of human dependency on coral reefs, which is currently lacking within the field of ecosystem services (Townsend et al., 2018). Additionally, the framework was designed to be adaptable to regional and national scales, with the adaptability to add/substitute more indicators to human dependency categories with improved data.

Ultimately, I hope to reframe the thinking of human dependency from a liner scale, e.g. low to high dependency rankings, towards “how” countries are dependent on coral reefs, through creating human dependency “profiles”.

Limitations of the chapters

The chapters were not without its limitations, with using openly accessible databases the analyses are limited to the resolution of the data available. This could be the scale of the data and/or time of data collection and non-standardised methodologies being collated into one data frame or analysis.

The scale of extracting human population data on a global scale, over a 20-year time period had computational limitations. Extractions of data could take up to a week per year, therefore during the time of the analyses a new form of coral reef atlas was released but it was not reasonable to begin completing new analyses given any PhD's time limitations. Additionally, the conceptual human dependency framework proved to be to missing data in both the HDCRI and hybrid learning methods. However, this was an obstacle to be expected due to complete global datasets being difficult to come by as each country collects data independently.

Recommendations for future research

I hope that human population by coral reef statistics will continually be updated, not only with new population or census data, but additionally, with the improvements of global coral reef maps are available. Additionally, that our methodology will be applied at finer scales for national, city, or even "reef" scaled assessments and research. I also recommend that these human population values are integrated into human dependency research. I would hope that a global map of human populations at low elevations near coral reefs will be extracted to further refine analysis of the numbers of people we expect to be at risk near coral reefs due to climate change. For example, studies that focus on risk to future human populations due to climate change predictions which could potentially incorporate simulations from the CIMP6 models used in the IPCC Sixth Assessment Report (IPCC, 2021).

I have displayed that human dependency is non-linear and profiles of dependency are driven by a number of factors. I recommend that the conceptual human dependency framework, is continually improved with improved data availability. Additionally, I hope this would be integrated into a formal standardised methodology for assessing human dependency on coral reefs and extended to other marine ecosystems.

The outputs from both chapters are aimed at coral reef scientists, managers and policymakers. I hope that informed decisions can be made when distributing resources and funding in conservation and/or climate change mitigation. Finally, to be utilised in novel climate resilience methods, such as index-based insurance policies.

Conclusion

To conclude these studies have made available a comprehensive list of coral reef countries and global long-term dataset of human populations near coral reefs spanning a 20-year time period from 2000 to 2020. We discovered that nearly a billion people lived within 100 km of coral reefs in 2020, and given increased population predictions by coastlines, that number will rise. Additionally, I provided a conceptual human dependency on coral reefs framework that uses multiple statistical methods to create human dependency profiles. With these dependency profiles I aim to reframe the thought around human dependency on coral reefs and lead to a standardised methodology in human dependency research.

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