Received: 21 February 2022 | Revised: 28 July 2022 | Accepted: 31 July 2022

DOI: 10.1111/gcb.16391

RESEARCH ARTICLE

Global Change Biology WILEY

An assessment of people living by coral reefs over space and time

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Abstract

Human populations near ecosystems are used as both a proxy for dependency on ecosystems, and conversely to estimate threats. Consequently, 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 along with population proportion, using freely available data sets and replicable methods. We present trends of changes in human populations living near coral reefs over a 20-year time period (2000–2020), divided by region and country, along with socio-economic denominations such as country income category and Small Island Developing States (SIDS). 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 with 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. There are 60 countries with 100% of their population within 100 km of coral reefs. 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 4× the global average. From 5 to 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 reef management, coral reefs, global coral reef assessment, human population trends, marine conservation, marine policy

1 | 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, Department of Economic and Social Affairs, Population Division, 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, Department of Economic and Social Affairs, Population Division, 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 (Samir & Lutz, 2017).

Coastal zones are particularly important for human settlements and have been regarded as hot spots for habitation (Andrew et al., 2019). 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., 2015).

Of particular interest are Small Island Developing States (SIDS), where the dependency on marine ecosystems are particularly high. These populations are recognized as a special group of countries that are disproportionately vulnerable to climate change (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 recognized services provide livelihoods and welfare to the human populations which surround and use coral reefs globally (Frieler et al., 2013; Hughes 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 (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, for example, 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 and 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, 2018). This will have a devastating effect on the diversity of coral reefs and their inhabitants, which predominantly rely on the heterogeneity of reef-building corals in all their forms (Hoegh-Guldberg et al., 2019). 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; Wilkinson, 2004). Additionally, distance from the coast is an important factor in understanding risks and/or dependency in these coastal populations (Andrew et al., 2019). 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 standardized 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., 2011) 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 1). 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 help 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 human populations against climate change.

2 | METHODOLOGY

2.1 | Data collection and manipulation

Coral reef countries were obtained from literature and compiled as a comprehensive data set 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., 2019), additionally, populations within this area are more likely to derive or depend on coral reefs for their livelihoods and food reliance (Burke et al., 2011). The minimum distance of extraction was 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., 2011)—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.

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 1c). 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 data sets; a comprehensive list is provided in Appendix 1, including information on the region, sovereignty, ISO3, and ISO2 codes (The World Bank, 2018; United Nations, 2020). Coral country spatial data were obtained from the world data set from the GADM database (Lloyd et al., 2017) and imported into R for further analysis.

TABLE 1 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[a]	284,300[b]	Digitized 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[a]	152,478.6[c]	Sentinel-2 remote sensor images	Hedley et al. (2018)

Note: NA—data not available or stated in the study.
[a]Listed countries included territories of grouped countries.
[b]Referred to as conservative estimate (Wilkinson, 2004).
[c]Coral reef area covered by the Sentinel-2 data.

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 data sets provided by Oak Ridge National Laboratory. The data sets are at approximately 1 km (30″×30″) spatial resolution and represent an ambient population (average over 24 h) distribution (Bhaduri et al., 2002). LandScan data from 2000 to 2020 were downloaded from the LandScan website.

2.2 | Data analysis

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

2.2.1 | Population statistics

The total populations near coral reefs were extracted from LandScan (Bhaduri et al., 2002) data sets for the years 2000 to 2020. Distance from reef was classified into five distance categories: 5, 10, 30, 50, and 100 km adapted from Burke et al. (2011) and Andrew et al. (2019). Spatial buffers of coral reefs were created for each distance category (Figure 2). The buffers were used to extract the total population of each coral reef country, within each distance category, and across time from the LandScan data sets. 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 with country population growth. LandScan does not recommend using their data sets 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 compared with 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 1a), and country level, with additional groupings of income group (Figure 1b) and SIDS (Figure 1c). Regions were adapted from Burke et al. (2011), 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 (SI).

2.2.2 | R workflow: Population extraction

Points and polygons of global coral reef distribution spatial data (UNEP-WCMC) were summarized 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 data set. 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. The buffer data were 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 were used to extract population data from Landscan data sets 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.

3 | RESULTS

3.1 | 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 S2). 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).

At 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

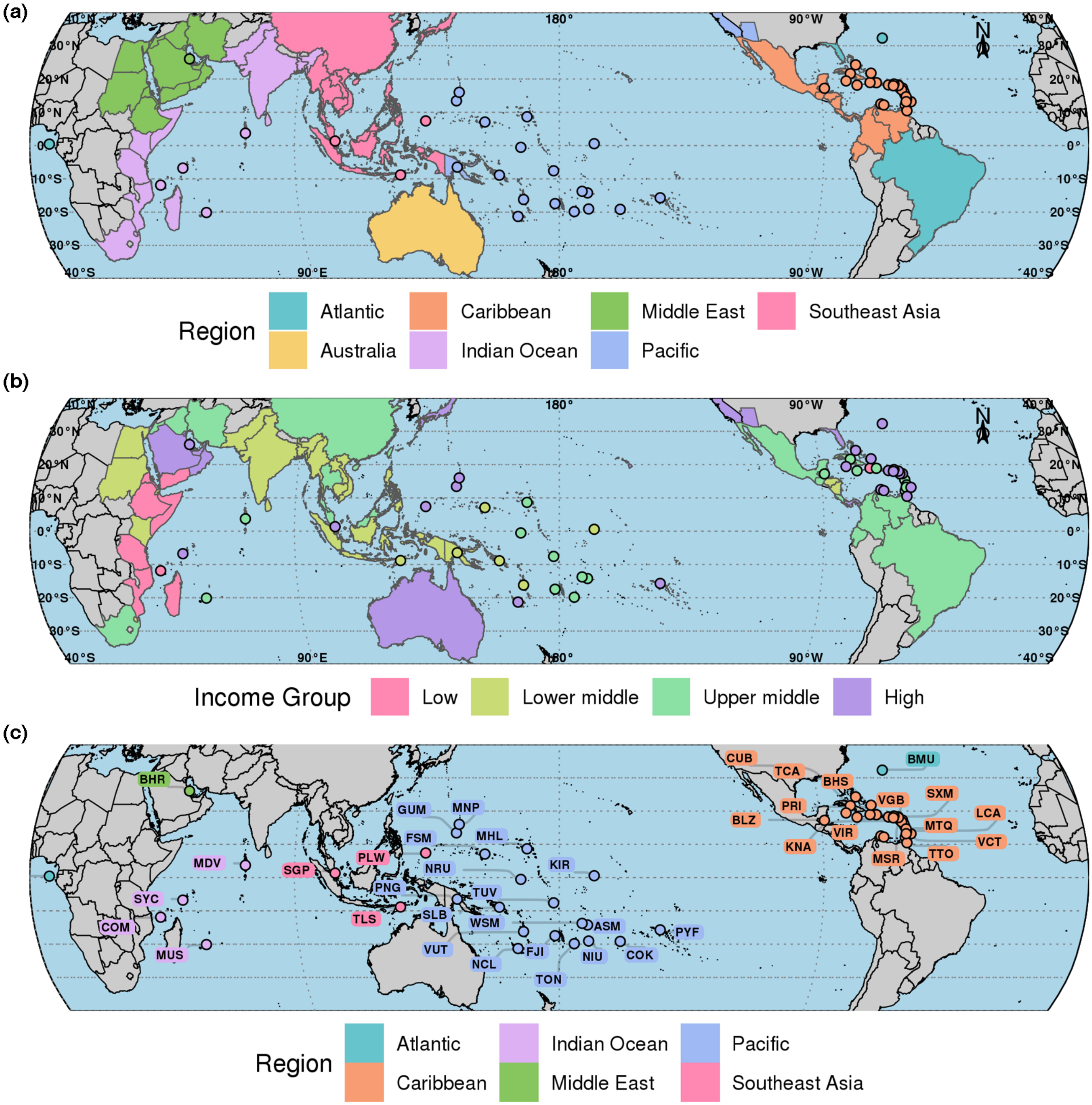

FIGURE 1 Coral reef countries (a) colored by regional groupings, (b) colored by income groupings and, (c) Small Island Developing States classified coral reef countries, colored by regional groupings, labeled with country ISO3 code (see Table S3 for country names and corresponding ISO3 codes). Points highlighting small island countries. Map lines delineate study areas and do not necessarily depict accepted national boundaries.

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 S7).

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 S4); 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 three coral reef countries across all distances and over the years considered here (Atlantic: Brazil, Bermuda and USA—Florida, Australia: Australia, Cocos [Keeling] Islands and Christmas Island). 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 S5).

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 and 9, lower-middle-income groups 19–23, upper-middle-income

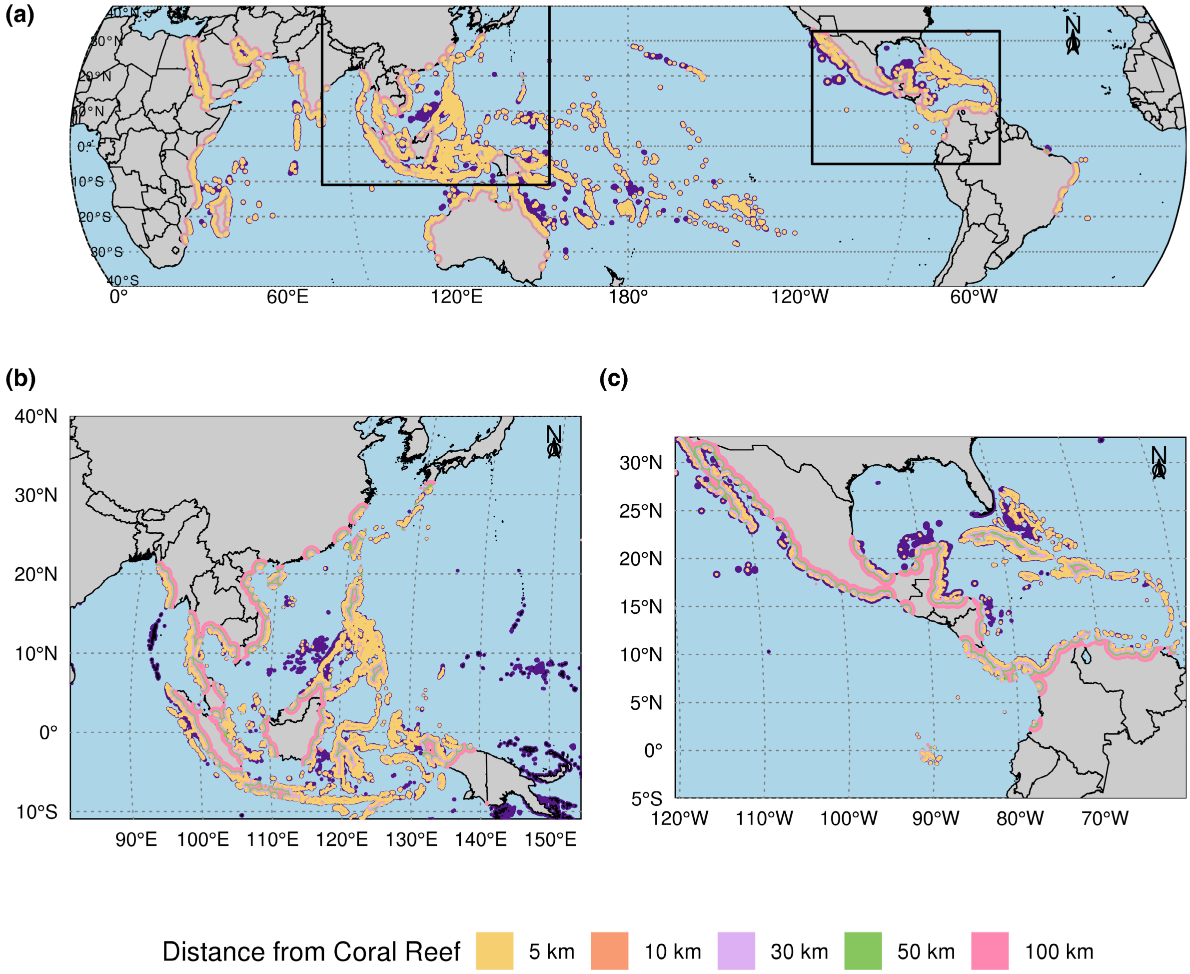

FIGURE 2 Map of buffers created around the (a) global distribution, (b) Southeast Asia and, (c) Caribbean regions of coral reefs (purple) at 5, 10, 30, 50, and, 100 km. Map lines delineate study areas and do not necessarily depict accepted national boundaries.

groups 31–32 and, high-income groups 36–37 coral reef countries (Table S6). Out of a total of 58 SIDS on the UN list, 54 are coral reef countries (Table S3), with a total of 53 SIDS included in this study (as coral reefs in São Tomé and Príncipe are not mapped).

3.2 | Populations near coral reefs

3.2.1 | Global population

Overall, total populations near coral reefs have increased steadily over time across all distance categories (Figure 3b). Populations within 100 km of coral reefs expanded from 762 million people in 2000 to 997 million people in 2020 (Figure 3b); this equates to 12.56% and 12.84% of the global population, respectively (Figure 3a). 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 with a 30.77% increase in populations within 100 km of coral reefs (Table S8). 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 3c). 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 S8).

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 between the years 2000 and 2020 (Table S8). The average population growth between 2000 and 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 S3).

3.2.2 | Regional populations

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

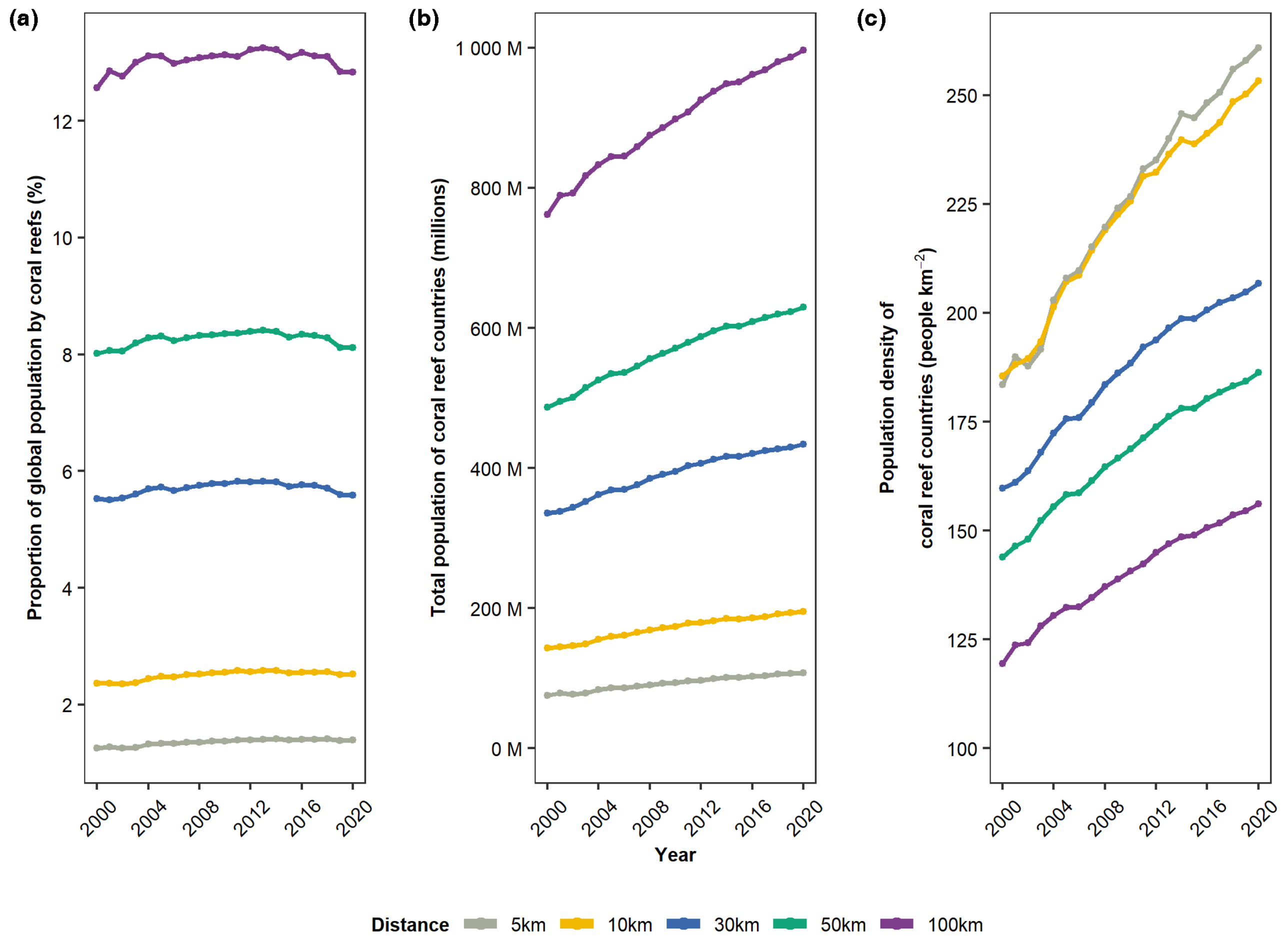

FIGURE 3 Global population proportion (%) (a), total population (b) and, population density (c) of people living within 5, 10, 30, 50, and 100 km from coral reefs between 2000 and 2020.

population living by coral reefs (Figure 4b). 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.

Table 2 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 to 2020. At 100 km in 2020, Australia and the Caribbean have the highest proportion of population living by coral reefs compared with the whole country population, at 37.10% and 35.86% respectively. At 10 km human populations in the Pacific have the highest population proportion by coral reefs at 47.17% 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 global 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 S9.

3.2.3 | Income groups

Compared with 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 5b). Low-income group countries have the highest population proportion between 5 and 10 km, with high-income groups overtaking at 30 km (Figure 5a). 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 5a) 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,

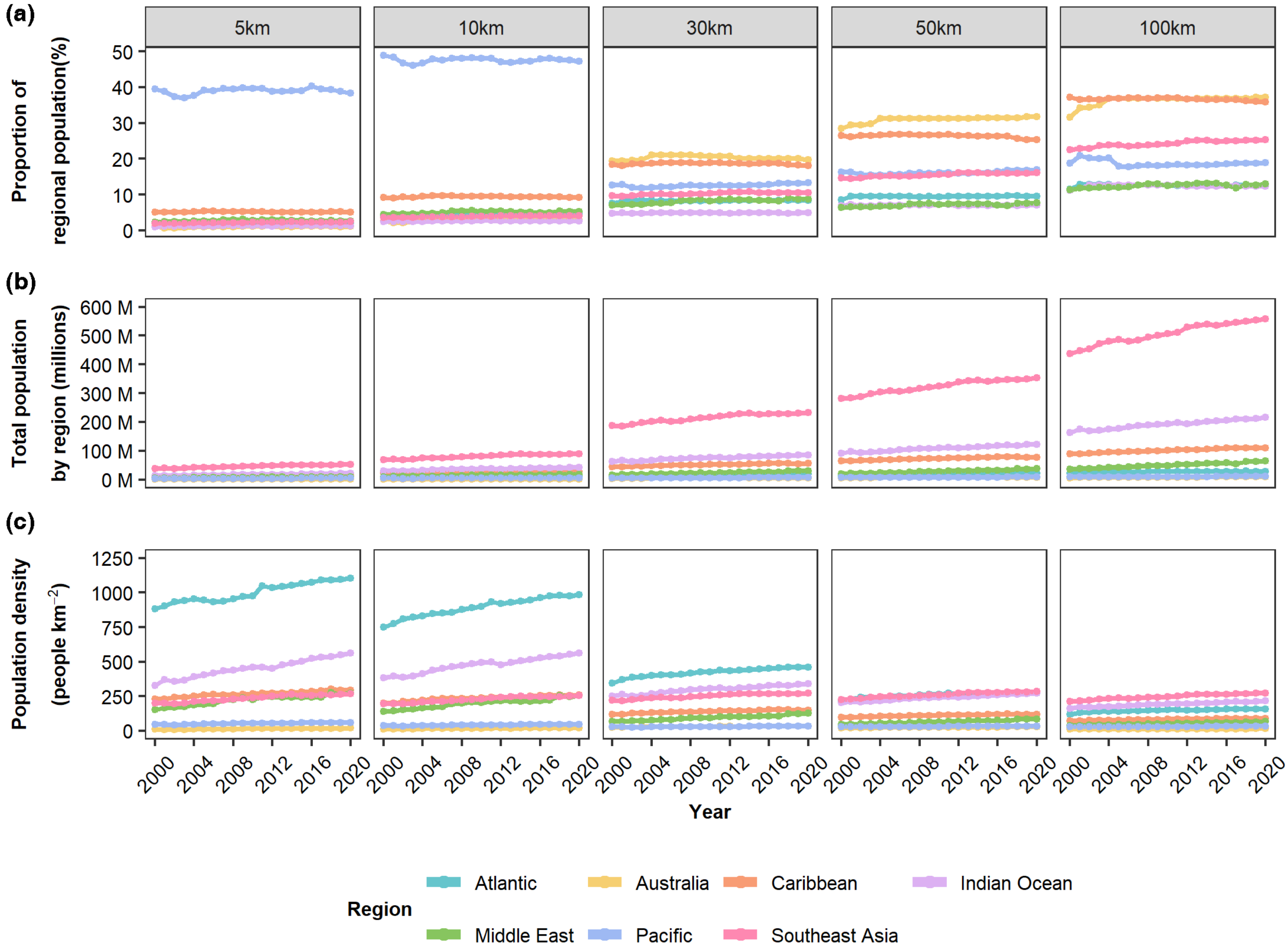

FIGURE 4 Regional population proportion of coral reef countries (%) (a), total population of coral reef countries by region (b) and, population density of coral reef countries by region (c) of people living within 5, 10, 30, 50, and 100 km from coral reefs between 2000 and 2020.

equating to a 24.73% increase (Table S10). 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 S10).

In upper-middle-income countries, there was a 35.40% increase in populations living within 100 km 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 5c). Between 30 and 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 with 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.

3.2.4 | Small Island Developing States

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 6b). 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 6a).

TABLE 2 Summary of regional populations statistics at 5 km and 100 km from 2000 to 2020 (all distances available in Table S9)

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

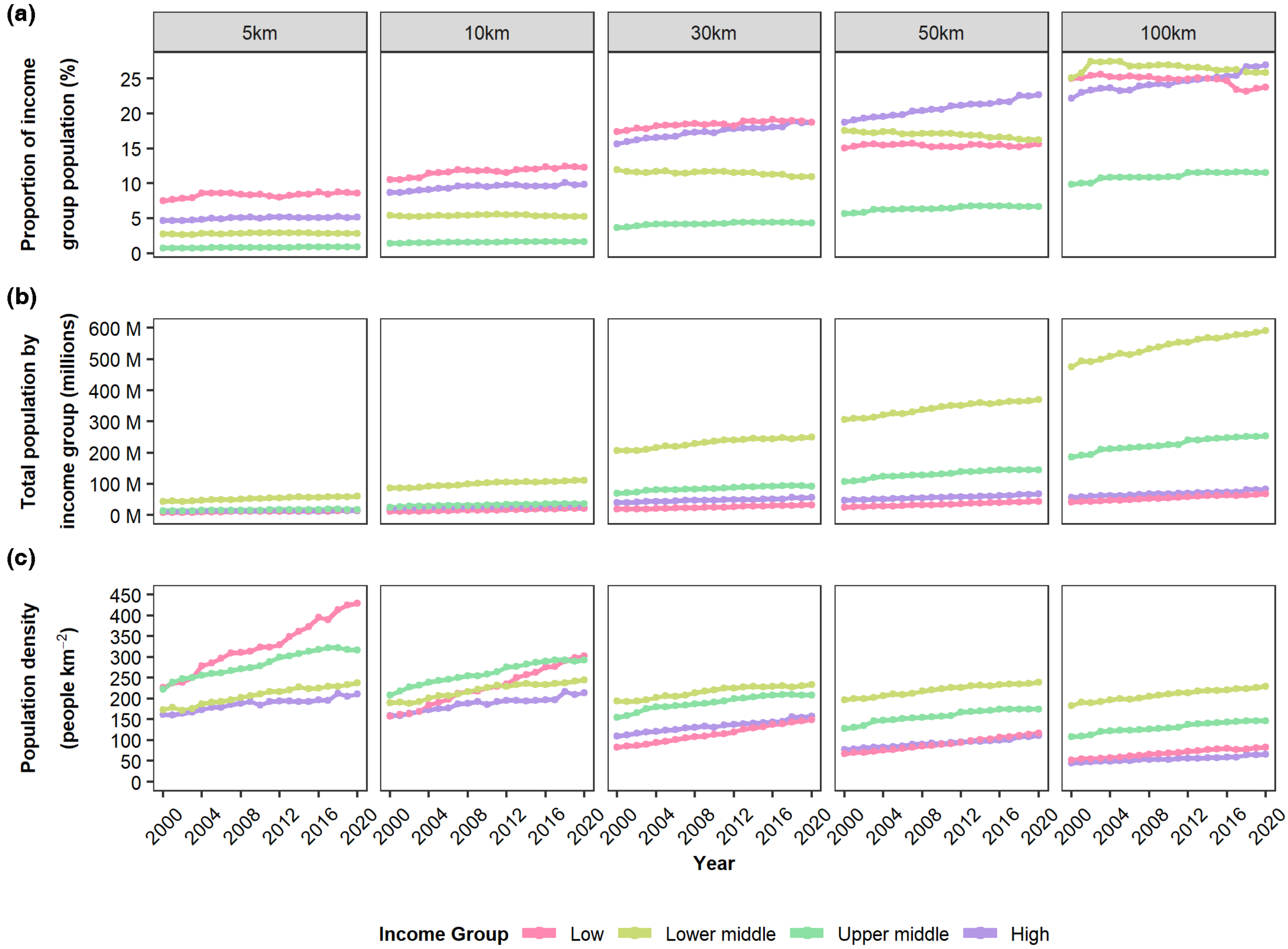

FIGURE 5 Income group population proportion (%) (a), total population (b) and, population density (c) of people living within 5, 10, 30, 50, and 100 km from coral reefs between 2000 and 2020.

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 S11). 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 6c), notably from 2014 when population density at 5 km became higher than populations at 10 km.

3.2.5 | 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 S12), 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 S1); 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 2020 (Figure S1a). Indonesia, the Philippines, and India were ranked first, second, and third for the total population that lives within 30 to 50 km of a coral reef (Figure S1c,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 S2a,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 third and second for population density by coral reefs at 5 and 10 km, respectively, and Singapore ranked first at 10 to 50 km (Figure S2a,b).

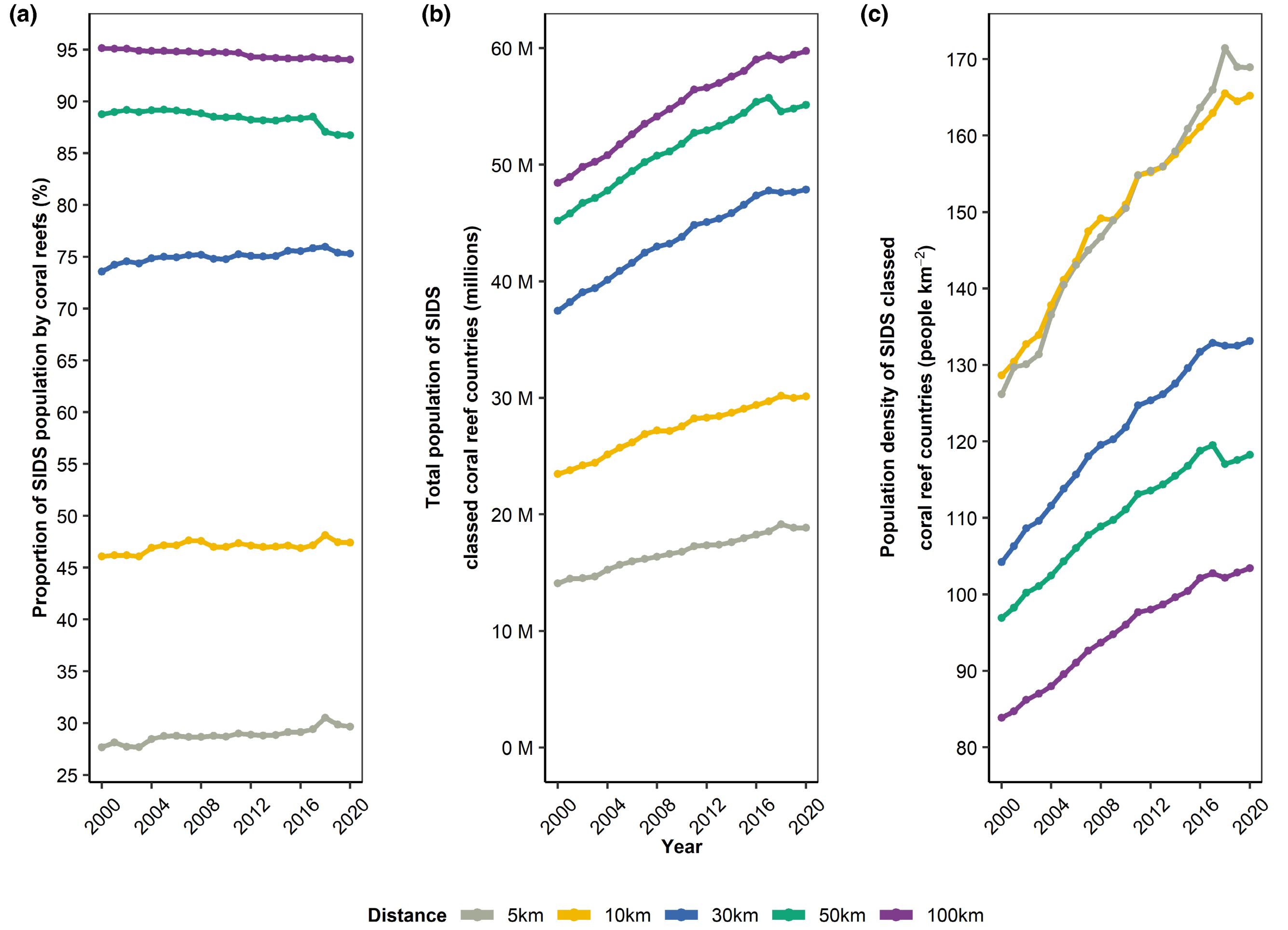

FIGURE 6 Small Island Developing States population proportion (%) (a), total population (b) and, population density (c) of people living within 5, 10, 30, 50, and 100 km from coral reefs between 2000 and 2020.

4 | 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., 2011). 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 background coastal population trends (Barbier, 2014b; Creel, 2003; Neumann et al., 2015; The World Bank, 2018). Coral reef population density was four times higher between 5 and 10 km from coral reefs compared with the global average; between 30 and 100 km from coral reefs population density was around three 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., 2015). 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 more than 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 (Wilkinson, 2004).

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. (2019) 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 impacts 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 toward tourism began in the 2000s (Burt & Bartholomew, 2019).

Regional population density was extremely high in the Atlantic between 5 and 10 km from coral reefs. This region encompasses three coral reef countries; Brazil, Bermuda, and the state of Florida in the United States (Figure S7f). 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); the five counties in Southeast Florida that border these reefs having populations greater than 31 other US 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 are 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 2020; 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 and 30 km of coral reefs compared with 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 with 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 characterized 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 (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; 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., 2019), 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.

4.1 | 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 100km 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 (Cinner et al., 2018).

AUTHOR CONTRIBUTIONS

Michelle L. Taylor and Amy Sing Wong contributed to the study design; Amy Sing Wong curated the data and performed the analysis. Spyridon Vrontos contributed to analysis design. Amy Sing Wong wrote the original draft. Michelle L. Taylor and Amy Sing Wong reviewed and edited subsequent drafts.

ACKNOWLEDGMENTS

The authors would like to thank the University of Essex for funding the study through the Faculty Research Studentship, and UNEP-WCMC for early discussions and feedback on this study; and Cain Gill for assistance with conceptualising the graphical abstract. We also thank the reviewers for their comments during the peer review, which greatly improved the manuscript.

CONFLICT OF INTEREST

We declare that there are no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data and code for analysis are publicly accessible at https://github.com/amysw13/human_populations_by_coral_reefs and at Zenodo at https://zenodo.org/badge/latestdoi/510611252.

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SUPPORTING INFORMATION

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How to cite this article: Sing Wong, A., Vrontos, S., & Taylor, M. L. (2022). An assessment of people living by coral reefs over space and time. *Global Change Biology*, *28*, 7139–7153. https://doi.org/10.1111/gcb.16391