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Global decline in capacity of coral reefs to provide ecosystem services

Highlights

- Coral reef habitat, biodiversity, fisheries, effort, and food-web impacts are evaluated
- Global coverage of living coral has declined by half since the 1950s
- Catch of coral reef associate fishes per unit effort has decreased by 60% since 1950
- Coral reefs' capacity to provide ecosystem services has declined by half since the 1950s

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In brief

Coral reefs are known to be important habitats for biodiversity and are particularly sensitive to climate change because marine heatwaves can cause bleaching events. Coral reefs also provide important ecosystem services to humans, through fisheries, economic opportunities, and protection from storms. What is unknown is how global coral reef habitat and the capacity to provide ecosystem services has changed through time. We have provided the first estimate of this decline and demonstrate how at risk these services are.

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Global decline in capacity of coral reefs to provide ecosystem services

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SCIENCE FOR SOCIETY Coral reef ecosystems are important for tropical and subtropical coastal communities, small-island developing states, and Indigenous peoples because they provide ecosystem services such as food provision, livelihood opportunities, carbon sequestration, and protection from storms. We have derived global estimates of key ecosystem services provided by coral reefs: catches of coral-reef-associated fishes, abundance of coral-reef-associated fishes, coral-reef-associated biodiversity, and consumption of coral-reef-associated fishes by Indigenous peoples. Our study indicates that the capacity of coral reefs to provide ecosystem services that are relied on by millions of people worldwide has declined by half since the 1950s. Achieving climate-change-emissions targets and reducing local impacts can reduce stress on coral reefs, allowing them and the ecosystem services that they provide to persist.

SUMMARY

Coral reefs worldwide are facing impacts from climate change, overfishing, habitat destruction, and pollution. The cumulative effect of these impacts on global capacity of coral reefs to provide ecosystem services is unknown. Here, we evaluate global changes in extent of coral reef habitat, coral reef fishery catches and effort, Indigenous consumption of coral reef fishes, and coral-reef-associated biodiversity. Global coverage of living coral has declined by half since the 1950s. Catches of coral-reef-associated fishes peaked in 2002 and are in decline despite increasing fishing effort, and catch-per-unit effort has decreased by 60% since 1950. At least 63% of coral-reef-associated biodiversity has declined with loss of coral extent. With projected continued degradation of coral reefs and associated loss of biodiversity and fisheries catches, the well-being and sustainable coastal development of human communities that depend on coral reef ecosystem services are threatened.

INTRODUCTION

Coral reefs are biodiversity hotspots that provide millions of people with ecosystem services such as food provision, livelihood opportunities, carbon sequestration, and buffering against extreme climate events.[3–16] The capacity of coral reefs to provide these services can change on millennial timescales with natural fluctuations in environmental conditions or on decadal timescales due to anthropogenic stressors such as overfishing, pollution, habitat destruction, and climate change.[7,17–19] Understanding the impacts of these stressors on the ocean's capacity to provide ecosystem services is important for transitioning to a sustainable blue economy,[20] establishing recovery targets,[8,21] achieving the United Nations (UN) sustainable development goals (SDGs),[22] and anticipating where and how future societies will be impacted under socio-economic and greenhouse-gas-emissions scenarios.[22,23]

There are an estimated 6 million coral reef fishers worldwide,[24] and coral reef fisheries are valued at USD 6 billion.[25] Coastal Indigenous peoples have essential cultural relationships with coral reef ecosystems, and their consumption of seafood is 15 times higher than that of non-Indigenous populations.[2] Fish is

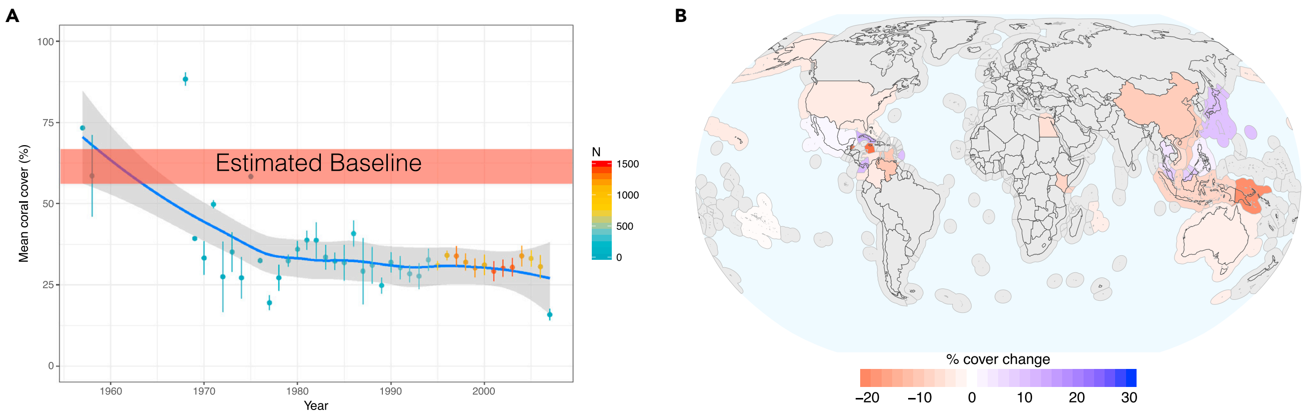

Figure 1. Global coral reef cover trends

(A) Global hard coral mean percent cover weighted by area of coral reef in each EEZ. "Estimated baseline" is the percent range for the 1950s indicated by experts in a global survey.[8]

(B) Change in percent coral cover from the first five years of the time series to the last five years of the time series by EEZ.

an important source of nutrition for people in small-island developing states (SIDSs),[26] comprising 50%–90% of dietary animal protein in Pacific Island countries and territories,[27] 50% in west Africa,[4,28] and 37% in southeast Asia.[22,29] In these regions, fish are an important source of micronutrients, such as iron, zinc, and omega-3 fatty acids.[4] There is increased recognition and need to contextualize efforts and challenges with ensuring protection and restoration of tropical marine ecosystems, notably coral reefs.

In recent studies, this has included global analyses of Indigenous-led initiatives to support sovereignty and nature conservation in traditional territories[30,31] and a wider recognition of the foundational efforts of SIDSs to redefine sustainable development approaches under a blue economy.[20,32] The global community has identified the importance of ecosystem services provided by coral reefs through its commitment to achieve targets associated with SDG2 (end hunger, achieve food security and improved nutrition, and promote sustainable agriculture) and SDG14 (conserve and sustainably use the oceans, seas, and marine resources for sustainable development).

Coral cover on tropical reefs has declined substantially over the last 40 years.[6,8,33–35] Anthropogenic ocean warming has triggered mass bleaching and disease outbreaks, greatly reducing the extent of coral cover of nearly all the world's tropical coral reefs.[6,35–38] Local drivers like pollution and overfishing are thought to contribute to coral loss in some locations;[39,40] however, these effects have been difficult to assess, measure, and quantify.[41,42] What remains unknown are the aggregated implications of these regional trends for the global capacity of coral reefs to provide ecosystem services for the millions of people who rely on them.[16,2,26]

Here, we provide a global analysis of trends in living coral cover, associated fishery catches and effort, balance of fishing across the food web, coral-reef-associated biodiversity, and seafood consumption by coastal Indigenous peoples. We combined datasets from coral reef surveys, estimated coral-reef-associated biodiversity, fishery catches and effort, fishery impacts on food-web structure, and Indigenous consumption of coral-reef-associated fish. Our analysis indicates that the capacity of coral reefs to provide ecosystem services has declined by about half globally. This study speaks to the importance of how we manage coral reefs not only at regional scales but also at the global scale and the livelihoods of communities that rely on them.

RESULTS

Coral cover

Overall, historical coral coverage was estimated to range from 58% to 70% in coral reef systems worldwide.[8] There has been approximately a 50% decline in coral reef cover globally from 1957–2007 (Figure 1A). There were only a few observations in the early part of the time series, which originated from the western Indian Ocean, indicating high uncertainty around what the average coral cover was during the mid-20th century. The effects of climate change worldwide started prior to this period, suggesting that the historical baseline could have been higher (Figures S1 and S2). The average decadal rate of loss in coral coverage during the study period ranged from 4.7% to 6.8% (Figure 1A). Most regions had relatively low sampling effort, except for countries in the western central Atlantic and the western central Pacific (Figure S1). Most countries showed declines in coral cover, although some countries in the Caribbean (Barbados, Cuba, Panama) and the western Pacific (Japan, Malaysia, Philippines, Thailand) showed increases based on available survey data (Figure 1B).

Biodiversity

Countries with the greatest coral-reef-associated biodiversity were typically found in the Pacific, although there was no clear separation among ocean basins (Figure 2A). We examined the species-area relationship[43] for coral-reef-associated organisms by the main taxonomic groups (macroalgae, macroinvertebrates, and fish). Regression (log-log linear) between the estimated area of coral and total species richness among exclusive economic zones (EEZs) (n = 94) showed a positive relationship with a slope of 0.30 (p = 4.98e-07) and an intercept of 1.58 (p = 1.04e-08), with

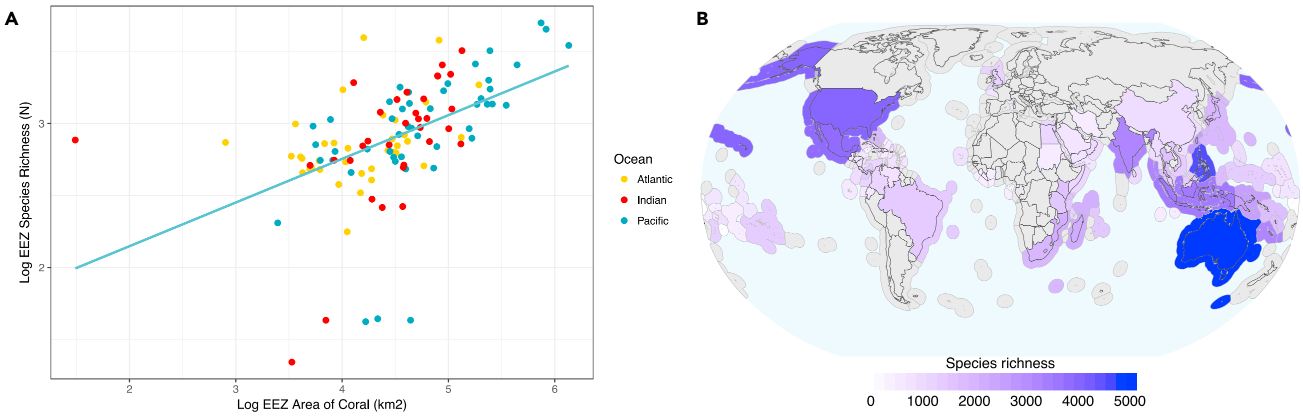

Figure 2. Global coral-reef-associated biodiversity

(A) Coral-reef-associated species richness per EEZ versus area of coral reef in each EEZ by ocean basin.

(B) Coral-reef-associated species richness by EEZ.

a Spearman coefficient of 0.63 (Figure 2B). Macroinvertebrates had a slope of 0.40, an intercept of 0.03 (p = 7.79e-06; p = 0.93, respectively), and a Spearman coefficient of 0.52. Fish had a slope of 0.30, an intercept of 0.70 (p = 2.88e-06; p = 0.01, respectively), and a Spearman coefficient of 0.52. Mammals had a slope of 0.09, an intercept of 0.95 (p = 0.01; p = 5.51e-09), and a Spearman coefficient of 0.28. We also subset EEZs that had a latitudinal centroid of coral reef area within the tropics and found that the species-area relationship increased for all groups, with a Spearman coefficient of 0.74.

Fisheries

Global catches of coral-reef-associated fish steadily increased from 1950 until they peaked at approximately 2.3 million tons in 2002, representing 2.0% of global catches, after which they steadily declined and represented 2.5% of global catches in 2010 (Figures 3A, S3, and S4). Global fishing effort for coral-reef-associated species in EEZs with coral reefs increased from 1950–2010 (Figure S5), and the resulting catch-per-unit effort (CPUE) trend peaked in 1971, after which it decreased—an indication of declining coral reef fish abundance in many countries (Figure 3B). The fishing in balance (FIB) index increased through time and then leveled off, indicating increasingly unbalanced removal of higher trophic-level species (Figure 4). The countries with the highest per-capita Indigenous consumption of coral reef fish—Palau, Micronesia, and Kiribati (Figure 5)—are SIDSs. Other areas with high per-capita consumption include eastern Africa, southeast Asia, and the Bay of Bengal (Figure 5). In these and other areas, the protection and state of social-ecological systems that provide local seafood from coral reefs is particularly pertinent given broader national food-security issues. For example, Palau has established new national policies related to seafood production and tourist consumption specifically to prioritize consumption of reef fishes for local Palauans and their traditional fisheries.[26]

DISCUSSION

Our study has aggregated regional trends of coral reefs to provide ecosystem services and demonstrated that the continuing decline of healthy coral reefs and the quality of habitat that they provide is contributing to a global decrease in provision of ecosystem services for the millions of people who rely on them. Particularly, our results highlight the erosion of biodiversity and food provision. The species-area relationship suggests a high sensitivity of species richness as a function of coral habitat. The estimated historical loss in coral habitat directly translates into loss in capacity of the remaining coral reefs to support biodiversity.[11,43] The decline in global CPUE, an index of relative abundance of coral-reef-associated fisheries resources, suggests a loss in the production potential of many fish stocks that are important sources of food, culture, and livelihoods for coastal dependent communities. Other studies have suggested that for some coral reefs, the mean trophic level of the community (an indication of top predators in an ecosystem) can increase with fishing pressure, because exploited lower trophic-level herbivores get replaced by middle trophic-level species.[45] We did not report this result, which could be due to only using fishery catches and not surveying unexploited species that make up the wider coral reef community as reported in Graham et al.[45] Our results highlight the sensitivity of coral reef ecosystems, because of their biology, as well as the high dependence on them by human communities.[23,46] Our study has also highlighted important data gaps that exist for many nations—improved monitoring and reporting for healthy coral reef coverage, associated biodiversity abundance, fisheries' catches and effort, and seafood consumption could reduce uncertainty in future coral reef ecosystem service analyses.

Essential measures that are defined and agreed targets of the SDGs, such as reducing overexploitation through effective fisheries management[47] (SDG 14.4, 14.7), encouraging ecosystem protection and restoration (SDG 14.2), and reducing export of silt and nutrient pollution to coastal waters (SDG 14.1) can help countries mitigate some of the local impacts (within their EEZs) to coral reefs and can simultaneously benefit other social concerns and development objectives.[48–51] However, climate change and ocean warming are the greatest threats to coral reef capacity, outweighing local stressors.[22,52,53] Coral reefs such as the Great Barrier Reef have been experiencing bleaching events at unprecedented frequency, threatening their persistence,[35,54] and recent research

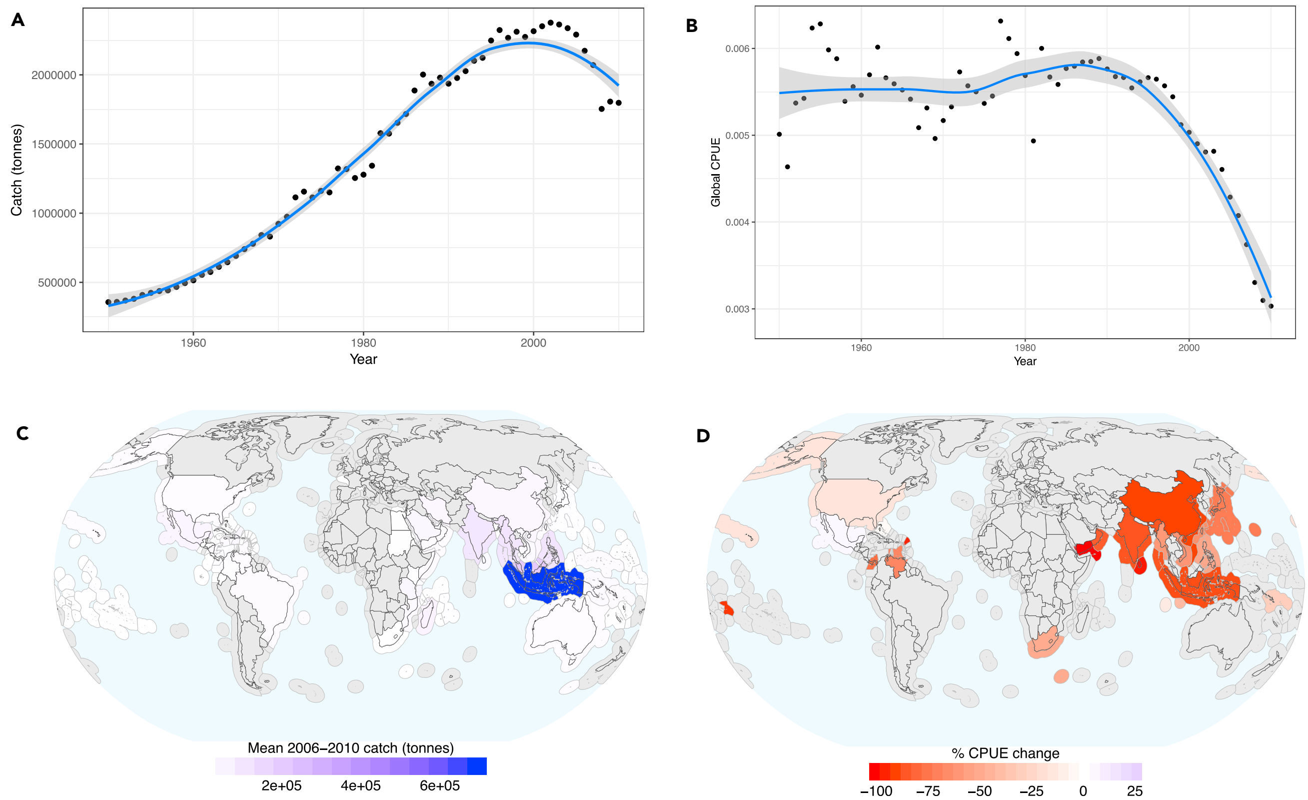

Figure 3. Global coral reef fisheries trends

(A) Global catches of coral-reef-associated fish.

(B) CPUE of coral-reef-associated fish.

(C) Mean annual catches of coral-reef-associated fish by EEZ from 2006–2010.

(D) Percent change in CPUE from the first five years of the time series compared to the last five years of the time series by EEZ.

suggests that the most vulnerable species of coral are increasingly rare, and the species that persist are more tolerant of warming conditions.[55,56] These observations fit with the global trend of decline in coral cover during the 1950s to 1970s, followed by a reduced decline since the 1980s (Figure 1A). There have been efforts to restore coral reefs by transplanting them, cooling them with underwater pumps, manipulating genome, and employing robots to spread coral larvae; however, nothing yet has shown promise to be effective at the landscape scale that would be required to make a meaningful impact. Protecting coral reefs and their ecosystem services will require strong cooperation across scales to reduce emissions and frequency of heat waves[57,58] and a deeper understanding of anthropogenic drivers and their effects.[59]

The effects of degraded and declining coral reefs are already evident through impacts on subsistence and commercial fisheries and tourism in Indonesia, the Caribbean, and South Pacific, even when marine-protected areas are present,[49,50] because they do not provide protection from climate change and could suffer from lack of enforcement[60,61] and marine-protected-area staff capacity.[62] Fish and fisheries provide essential micronutrients in coastal developing regions with few alternative sources of nutrition.[4] Coral reef biodiversity and fisheries take on added importance for Indigenous communities, SIDSs, and coastal populations where they could be essential to traditions and cultural practices.[2] The reduced capacity of coral reefs to provide ecosystem services undermines the well-being of millions of people with historical and continuing relationships with coral reef ecosystems.

Developing pathways and targets for recovery and climate adaptation requires a globally coordinated effort while also addressing needs and management at local scales.[58] Climate mitigation and adaptation actions as highlighted in the Paris Agreement are progressing but need to accompany other efforts to address direct and indirect drivers that are diminishing coral reef capacity. Such an approach is highlighted by recent collaborations between international institutions, exemplified by the joint report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) and the Intergovernmental Panel on Climate Change (IPCC) that calls for the need to address biodiversity, climate, and social challenges in an integrated manner.[62]

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for resources and reagents should be directed to and will be fulfilled by the lead contact, Tyler Eddy (tyler.eddy@mi.mun.ca).

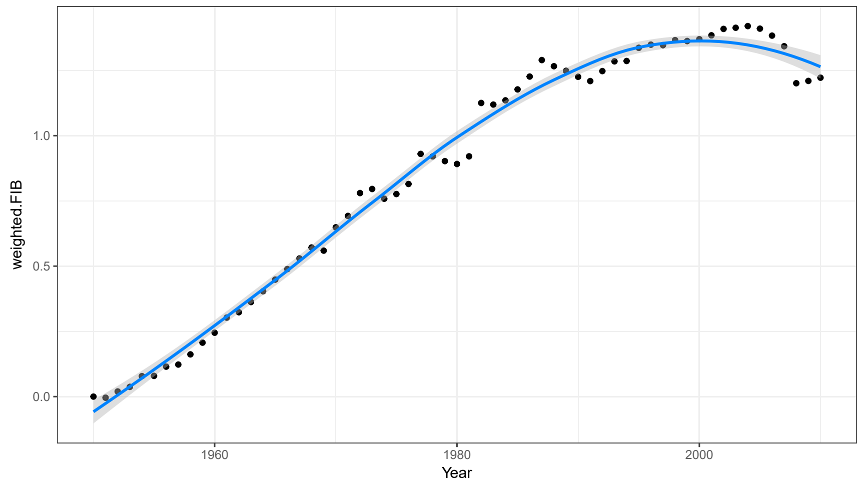

Figure 4. Global coral reef fisheries food-web impact

FIB index of coral-reef-associated fish in grid cells where coral reefs occur, weighted by EEZ area of coral reef habitat.

Materials availability

The datasets generated used in this study are available from the sources above.

Data and code availability

Coral cover data are publicly available from Bruno and Valdivia 2016.[1] Biodiversity data can be obtained from OBIS (www.iobis.org), GBIFF (www.gbif.org), and WCMC (www.unep-wcmc.org). Fisheries catch and effort data can be obtained from Sea Around Us (www.seaaroundus.org). Indigenous peoples' seafood consumption data can be obtained from Cisneros-Montemayor et al., 2016.[2]

Coral reef coverage observations

We used a database of coverage of reefs by living corals that included 14,705 surveys, from 3,582 reefs, in 87 countries in all major global coral reef regions, spanning 50 years from 1957–2007, an update of the database used in Bruno and Valdivia.[1] The number of observations for each survey from an individual site could be an average of observations during a particular year at that site, indicating that the actual number of observations was much greater than 14,705. In an ideal world, all sites would have been surveyed every year; however, that was not the case for this database. Rather than exclude sites and limit geographical coverage, we chose to include all data points. We recognize the bias that this introduces into our analysis; however, this comes with the benefit of substantially increasing the number of observations and geographical extent. Mean global coral percent cover was weighted by total area of coral per EEZ as reported by Sea Around Us,[44] such that observations in EEZs with greater coral reef area contributed more to the global average.

Coral reef cover expert surveys

Because pre-industrial observations of coral reef cover are rare, and it is difficult to understand the extent of modern-day declines,[21] Eddy et al.[8] created a survey and distributed it to coral reef scientists (n = 133). The survey asked the profession of the respondent, the first year that they had observed a coral reef, the highest coral cover that they had observed and where they had done so, and, lastly, their expert opinion on what the baseline average global coral reef cover might be in the absence of human impacts. We include this baseline in Figure 1A.

Biodiversity

To evaluate the relationship between coral reefs and associated marine biodiversity, we used a database of marine species occurrences.[63] Occurrence data originated from the Ocean Biogeographic Information System (OBIS - www.iobis.org); Intergovernmental Oceanographic Commission of UNESCO (IOC- ioc-unesco.org/); the Global Biodiversity Information Facility (GBIF - www.gbif.org), Fishbase (www.fishbase.org); the Coastal and Oceanic Plankton Ecology Production and Observation database (COPEPOD - www.st.nmfs.noaa.gov/plankton); the Jellyfish Database Initiative (http://dmoserv3.bco-dmo.org/jg/serv/BCO-DMO/JeDI/JeDI.brev0%7Bdir=dmoserv3.whoi.edu/jg/dir/BCO-DMO/JeDI/,info=dmoserv3.bco-dmo.org/jg/info/BCO-DMO/JeDI/JeDI%7D); and the International Union for the Conservation of Nature (IUCN - http://www.iucnredlist.org/technical-documents/spatial-data). The database contains over one billion sampling records and describes the distribution of 100,000 species from plankton to mammals. We developed a standardized database, which was populated with species data for which at least 10 spatially informed occurrences were available. After a standardization and data cleaning process,[63] geo-referenced occurrence records with sufficient information (i.e., reliable distributions) were quantified on a 100 km × 100 km equal area grid of the world's oceans.

Marine species (n = 42,315 species) with distributions located in global half-degree grid cells containing coral reefs as reported by Sea Around Us[44] were included (n = 3,689 of 150,000 global marine cells), from which we calculated species richness by EEZ. We also calculated species richness of macroalgae, phytoplankton, copepods, foraminifera, macroinvertebrates, fishes, and marine mammals. The area of coral reefs in each EEZ was calculated by using the area of half-degree grid cells that contain coral. To test whether the species-area relationship[43] held for our dataset, we used a log-linear regression of richness by EEZ and area of coral reef by EEZ, because the species-area relationship is a power law.

Catches and effort of coral-reef-associated fisheries

The Sea Around Us global reconstructed marine capture fisheries catch database[44] provided catches of coral-reef-associated fishes from half-degree grid cells that contained coral habitats[64] from 1950–2010. Sea Around Us also provided data on fishing effort by fishing country.[65] Fishing effort for coral-reef-associated fishes was estimated by using the ratio of the EEZ catch of coral-reef-associated fishes in grid cells that contain coral to the total catch in that EEZ, applied to the total fishing effort for the same EEZ. This estimation assumes that the ratio of catches of coral-reef-associated fishes to catches of all fishes is proportional to the fishing effort for coral-reef-associated fishes compared to total fisheries effort. The coral-reef-associated fish CPUE (an indicator of fish biomass) was then calculated. Fishing effort data from Sea Around Us was not available for all countries (n = 72; Figure 3D); however, the effort data for the countries included in the analysis accounted for 99.8% of catches of coral-reef-associated fishes.

Mean trophic index and fishing in balance index

The Sea Around Us catch database also provided data to calculate the mean trophic index (MTI[66]) and the mean trophic level (TL) of the catch, which can be used to detect "fishing down the food web."[67,68] High MTI values suggest that the catch is mostly composed of large sized predators (TL > 3). Low values suggest the dominance of smaller-sized primary or secondary consumers (TL range 2–3) in the catch. A time series of annual MTI values can help detect changes to the ecosystem induced by fishing.[62,69] However, trends showing the fishing down the food web effect can be masked by fisheries' expansion (geographic and/or gear efficiency) to improve the catch of high-trophic-level fishes, resulting in an increase in MTI.[70–72] Such masking is detected by using FIB index,[66,73] which compares the MTI and catch each year to those of an initial year, indicating whether a fishery is fishing proportionally across all trophic levels (balanced harvesting). Positive FIB values indicate fishing higher levels of the food web compared to initially,

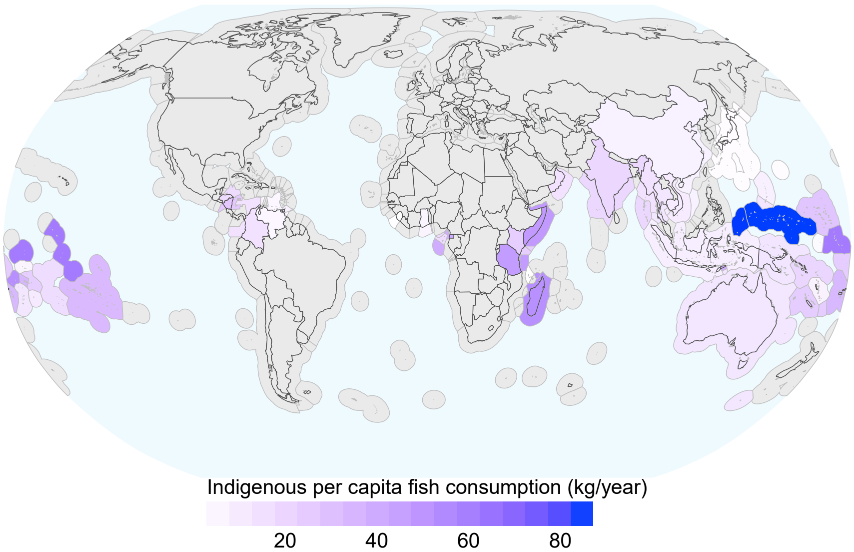

Figure 5. Consumption of coral-reef-associated fish by Indigenous communities by exclusive economic zone

Indigenous consumption data from Cisneros-Montemayor;[2] coral reef fish catch data from Sea Around Us.[44]

negative values indicate fishing lower, whereas values of 0 indicate fishing in balance.

Indigenous peoples' seafood consumption

We used a database of coastal Indigenous peoples' seafood consumption,[2] which was subset for EEZs that contained coral reefs. The database includes annual seafood consumption in kilograms per capita for over 1,900 coastal Indigenous communities but does not contain systematic information about the species of fish that were consumed. We therefore estimated the proportion of fish consumption that is coral-reef-associated fishes by using information from the Sea Around Us database, which includes total (Indigenous and non-Indigenous) subsistence catches from 1950–2014.[44] We used total subsistence catches by functional groups in EEZs that contain coral reefs and calculated the proportion of these catches that were coral-reef-associated fishes. We then applied these EEZ-specific mean ratios from 2010–2014 to the Indigenous seafood consumption data for communities in each EEZ. This approach makes the assumption that Indigenous communities living next to coral reefs source their subsistence catches from fish species associated with their local ecosystems.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2021.08.016.

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AUTHOR CONTRIBUTIONS

T.D.E., Y.O., and W.W.L.C. designed the research with support from all co-authors. T.D.E. and J.F.B. compiled and analyzed the coral reef cover database. T.D.E. and G.R. compiled and analyzed the biodiversity database. T.D.E., V.W.Y.L., K.G., and M.L.D.P. compiled and analyzed the fisheries database. T.D.E. and A.M.C.M. compiled and analyzed the Indigenous peoples' seafood consumption database. T.D.E. led the writing of the manuscript with contributions from all co-authors.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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