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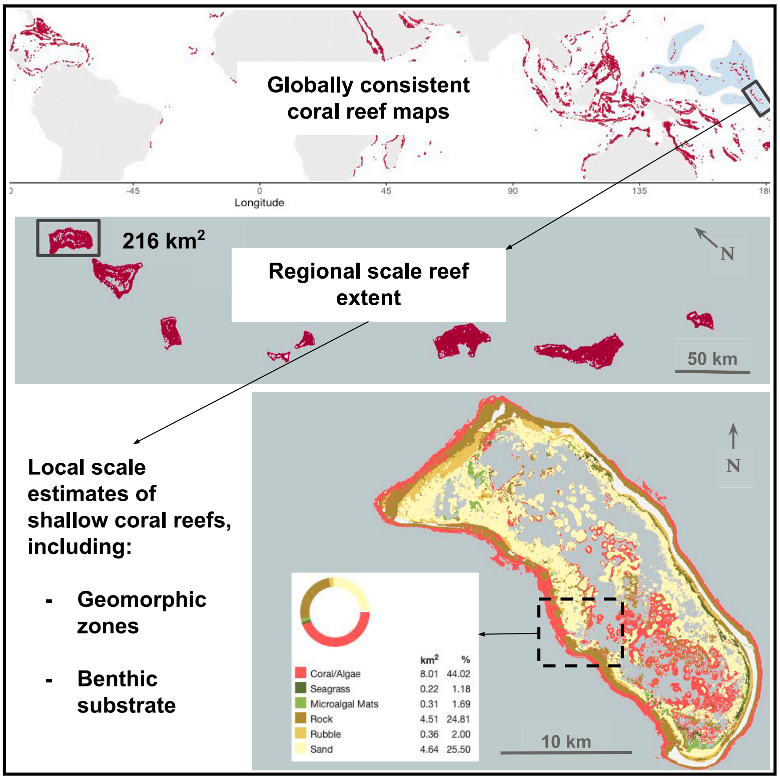
New global area estimates for coral reefs from high-resolution mapping

Graphical abstract



Highlights

- Statistics and trends from globally consistent high-resolution coral reef maps
- Global estimate of shallow coral reefs is 348,361 km^2, with 80,213 km^2 of coral habitat
- >480 data contributors, >1.5 million training samples, and 100 trillion satellite pixels
- Data are available on Allen Coral Atlas and Google Earth Engine

Authors

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In brief

Lyons et al. present statistics and trends derived from globally consistent, high-resolution maps of shallow coral reefs. They revise the global area of shallow corals reefs to 348,361 km^2, including 80,213 km^2 of coral habitat. Leveraging 1.5 million+ samples curated from 480+ data contributors and 100 trillion pixels from satellite imagery, this work integrates machine learning and coral reef science. Accessible publicly on the Allen Coral Atlas and Google Earth Engine, the data empower global efforts in coral reef conservation, management, and research.

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New global area estimates for coral reefs from high-resolution mapping

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SCIENCE FOR SOCIETY Coral reefs possess a quarter of all marine life and contribute to the well-being and livelihoods of a billion people worldwide. Maps of ecosystems underpin many science and conservation activities, but until recently, there were no consistent high-resolution maps of the world's coral reefs. In this paper, we describe new global coral reef maps from the Allen Coral Atlas, detailing the underlying methodology and our new understanding of the global distribution of coral reefs. The transparent and repeatable nature of our mapping framework allows the maps to be updated based on user feedback, and the ease of access has led to downstream applications such as coral bleaching monitoring and usage in scientific, management, and conservation activities. Hundreds of thousands of people have already accessed the maps, and they are already being used directly around the world for marine spatial planning, marine protected areas, environmental accounting and assessments, restoration, and education.

SUMMARY

Coral reefs underpin the environmental, social, and economic fabrics of much of the world's tropical coast. Yet, the fine-scale distribution and composition of coral reefs have never been reported consistently across the planet. Here, we present new area estimates enabled by global geomorphic zone and benthic substrate maps at 5 m pixel resolution. We revise global coral reef estimates to 348,361 km^2 of shallow coral reefs and 80,213 km^2 (46,237–106,319 km^2, 95% confidence interval) of coral habitat. The mapping used more than 1.5 million training samples supported by 480+ data contributions to deploy a coral reef classification of over 100 trillion pixels from the Sentinel-2 satellites and the Planet Dove CubeSat constellation. The publicly available maps are accessible via the Allen Coral Atlas and Google Earth Engine and are already being used by thousands of people to improve the conservation, management, and research of coral reef ecosystems.

INTRODUCTION

Coral reefs contain about a quarter of all marine life and support the physical, financial, and cultural livelihoods of around one billion people worldwide.[1,2] For a long time, we have understood that the health and welfare of both natural and human systems depend heavily on the ecosystem goods and services that coral reefs provide.[3,4] Despite good news stories and many localized examples of successful conservation efforts,[5] there is no doubt that coral reefs remain under serious threat worldwide.[6] High-resolution spatial information about their distribution and composition could improve many applications that use spatially explicit information. Spatial data underpin our calculations for ecosystem services like coastal protection[7] and their economic value for tourism.[8] Globally consistent maps can summarize the properties of marine protected areas that we know influence ecological and socioeconomic outcomes[9] and help us better predict the impacts of climate change.[10] More detailed maps can help us upscale biophysical models[11] and elucidate gaps in our understanding of reef health and condition.[12]

A review of the largest coral reef mapping project to date[13]—the Millennium Coral Reef Mapping Project—recommended that future global efforts should begin with a simple, transparent, and repeatable global coral reef product within which more detailed classes could be mapped. Another recent review[14] rightly asserted that one of the most fundamentally important yet unknown questions in reef ecology is how much coral the world's reefs possess. Previous global-scale coral reef mapping efforts were performed before global coverage of high-resolution imagery was available and before it was practical to implement a repeatable methodology globally.[15,16] High-resolution geomorphic and benthic mapping has been limited to local and regional scales.[17,18] No framework has yet been able to overcome the challenge of producing global coverage of locally detailed maps with a transparent and repeatable method. The Allen Coral Atlas[19] aimed to solve this global coral reef mapping challenge, developing globally consistent high-resolution map products for visible reef extent, geomorphic zones, and dominant benthic substrate (see map classification for mapping methods and class definitions).

We generated a global 5-m-pixel-resolution data stack from 1.17 million Planet Dove CubeSat images (between 2018 and 2020) and 1.05 million Sentinel-2 scenes as a basis for our mapping framework, within a global study area that encompassed coastal, nearshore, and offshore environments where tropical reefs can occur. Drawing information from over 100 trillion pixels acquired by these two earth observation programs, the data stack contained reflectance values, derived reflectance metrics, satellite-derived water depth (primarily from Sentinel-2 imagery[20]), and modeled wave environment.[21] Depth and waves are non-spectral variables that influence geomorphic zones and benthic substrate composition[21,22] and are thus highly informative resources for determining the distribution of reefs globally. We combined[21] the global data stack with a globally comprehensive training and validation database for the geomorphic (n = 1 million samples) and benthic (n = 600,000 samples) mapping classes. The samples were created by annotating high-resolution imagery, guided by 480 field datasets contributed by 400 individuals or groups.[23] The training data were used to train a machine learning classifier, which was subsequently tasked with predicting geomorphic and benthic class membership across the global study area. To manage regional variations in reef morphology, turbidity, and other environmental conditions, we implemented the mapping framework separately in 30 major coral reef regions. Each map output was subject to a suite of contextual and object-based post-processing procedures, customized for each mapping region. A globally comprehensive validation on the final map outputs, including full accuracy assessment and confidence intervals for each mapping region, was performed using held out validation data.

This paper acts as a scientific reference for the mapping framework and summary statistics for the Allen Coral Atlas. In summary, for shallow tropical reefs (−30° to 30° latitude) at 5-m-pixel resolution, we present: (1) their global extent and distribution, (2) the distribution of 11 geomorphic classes, and (3) the distribution of 6 benthic classes (Figure 1).

RESULTS AND DISCUSSION

Global summary of mapped areas

We mapped 410,285 km^2 of visible reef extent, of which 348,361 km^2 was able to be consistently defined as shallow coral reefs by classifying to a geomorphic zone and dominant benthic substrate class (Figure 2). The ability to summarize at different geomorphic and benthic levels provides deeper insight into the organization of coral reef environments from local to global-scale details (Figures 1, 2, and 3). We mapped 80,213 km^2 (46,237–106,319 km^2, 95% confidence interval) of coral habitat globally, indicating that only about a quarter of the global shallow coral reef area is likely to support significant amounts of coral. This provides a spatially comprehensive proof of various studies in the past that show this based on data from individual reefs or reef regions.[14,24] Seagrass is an important component of shallow coral reef ecosystems but has received little attention in global mapping efforts. We mapped 67,236 km^2 (53,408–100,293 km^2, 95% confidence interval) of seagrass meadows within our shallow coral reefs extent, one of the largest tropical seagrass mapping efforts to date.

A clear set of definitions for the above statistics is provided (Box 1) so that readers may correctly evaluate our new maps and area estimates. We recommend the shallow coral reefs area (348,361 km^2) be used as a general global estimate for "coral reefs," as it covers all shallow tropical areas where one might find coral, even if it is very sparse and the environment is not of biogenic origin. This is an increase on previous global-scale estimates of extent (284,300 km^2 from Spalding et al.[15]; 249,713 km^2 from Burke[25]; 154,049–301,110 km^2 from Li et al.[26]) because of our broader and more inclusive definition. The coral habitat area (80,213 km^2) should be used when explicitly trying to quantify the amount of area likely or able to support significant coverage of corals. This is supported by a previous global area estimate of "hard reef classes" (108,000 km^2; Andréfouët et al.[27]) that was extrapolated using an empirically derived fraction applied to the WCMCv4[15] reef area total.

High-resolution spatial data on the distribution of geomorphic zones and dominant benthic substrates enable novel analyses of extent, distribution, and structure at local to global scales. Our new maps will update knowledge of previously poorly known reef regions, while providing a consistent basis for reporting at customizable geo-political scales to support, for instance, marine spatial planning and assessments of national environmental ecosystem accounts or conservation targets. Customizations can include reef region to individual reef level (Figure 1), summaries by country/territory (Tables 1 and S1), and global-scale representations at various thematic specifications (Figure 2). Detailed composition comparison among any geographical boundaries can also be performed (Figure 3), with a potential opportunity for monitoring predicted impacts like increased rubble cover.[28]

Regional trends and comparisons

One of the fundamental motivations for a globally consistent mapping method was to build capacity for more detailed assessments of regions where only extent boundaries were known. Our previous understanding of the global distribution of coral reefs

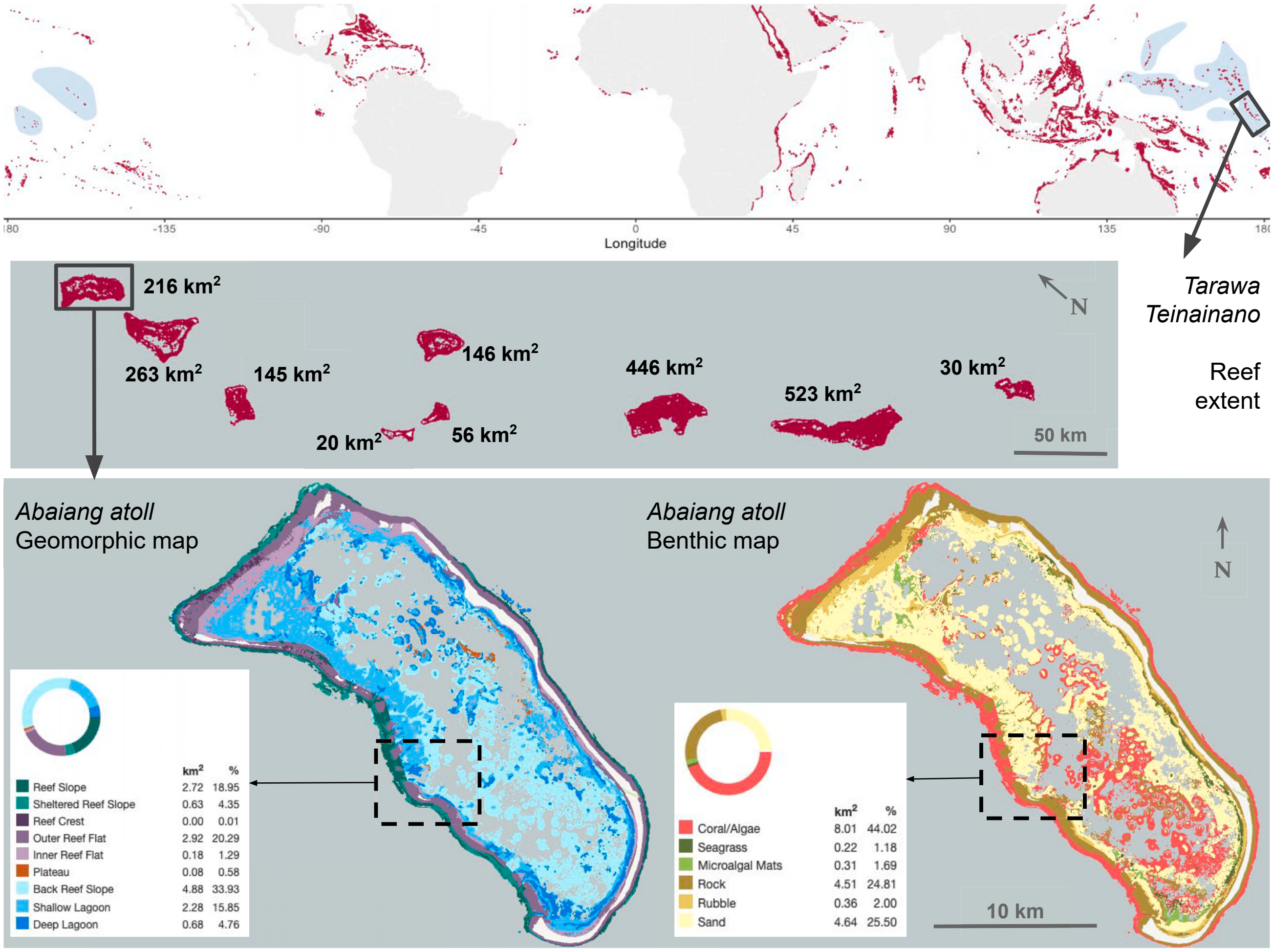

Figure 1. Consistent global maps of the world's shallow coral reefs

The top panel shows mapped shallow coral reef within the study area, with the Micronesia geographical region highlighted in light blue. The middle panel shows the reef extent areas for the Tarawa Teinainano islets, the capital of the Republic of Kiribati. The bottom two panels show an example of the 5-m-resolution geomorphic zonation and benthic substrate maps (for Abaiang atoll, Kiribati) that were created for every shallow coral reef in the world.

was largely built upon the Millennium Coral Reef Mapping Project.[13] These previous maps still represent the most detailed regional-scale habitat maps across large areas, but they do not contain benthic substrate information and several regions have no detailed geomorphology (notably Indonesia, Papua New Guinea, Philippines) or were not mapped (notably Australia, Red Sea). A lack of consistent definitions across a global-scale product like the WCMCv4 layer[13,15] has hindered globally consistent assessment methods.

Consider two major coral reef jurisdictions in the world, Australia and Indonesia, both of which had no previous detailed geomorphic or benthic mapping. Our maps show Australia to have 28,233 km^2 of shallow coral reefs and Indonesia to have 32,310 km^2, aligning with previous findings that they have a similar total area of reef.[15] However, our benthic substrate map reveals that Australia has about half the area of coral habitat compared with Indonesia (9,416 vs. 17,992 km^2; Table 1). We extended this concept globally, analyzed where there are hotspots of shallow coral reef vs. where there are hotspots of coral habitat (Figure 2), and plotted the relative composition of benthic substrate for the world's major coral reef regions (Figure 3). Although the shallow coral reef hotspots are distributed globally, the coral habitat hotspots are clearly concentrated around the Central Indo-Pacific—where species richness peaks for marine organisms in a well-known but poorly understood phenomenon.[29] Globally consistent information on composition will improve our understanding in regions where previously only reef boundaries were mapped, filling in knowledge gaps on global reef distribution (Figures S1 and S2; Table S1).

As the global-scale inventory of the coastal habitat mosaic continues to improve,[30–34] increased spatial and thematic resolution of coral reefs maps will aid conservation activities and spatially driven assessments.[35,36] Enhanced thematic resolution in our underlying map products is therefore crucial. We analyzed two countries with similar climate change risk profiles[37]: the Philippines (15,097 km^2 mapped), and the Bahamas (107,448 km^2 mapped). The Bahamas has over seven times the area of shallow coral reefs mapped compared with the

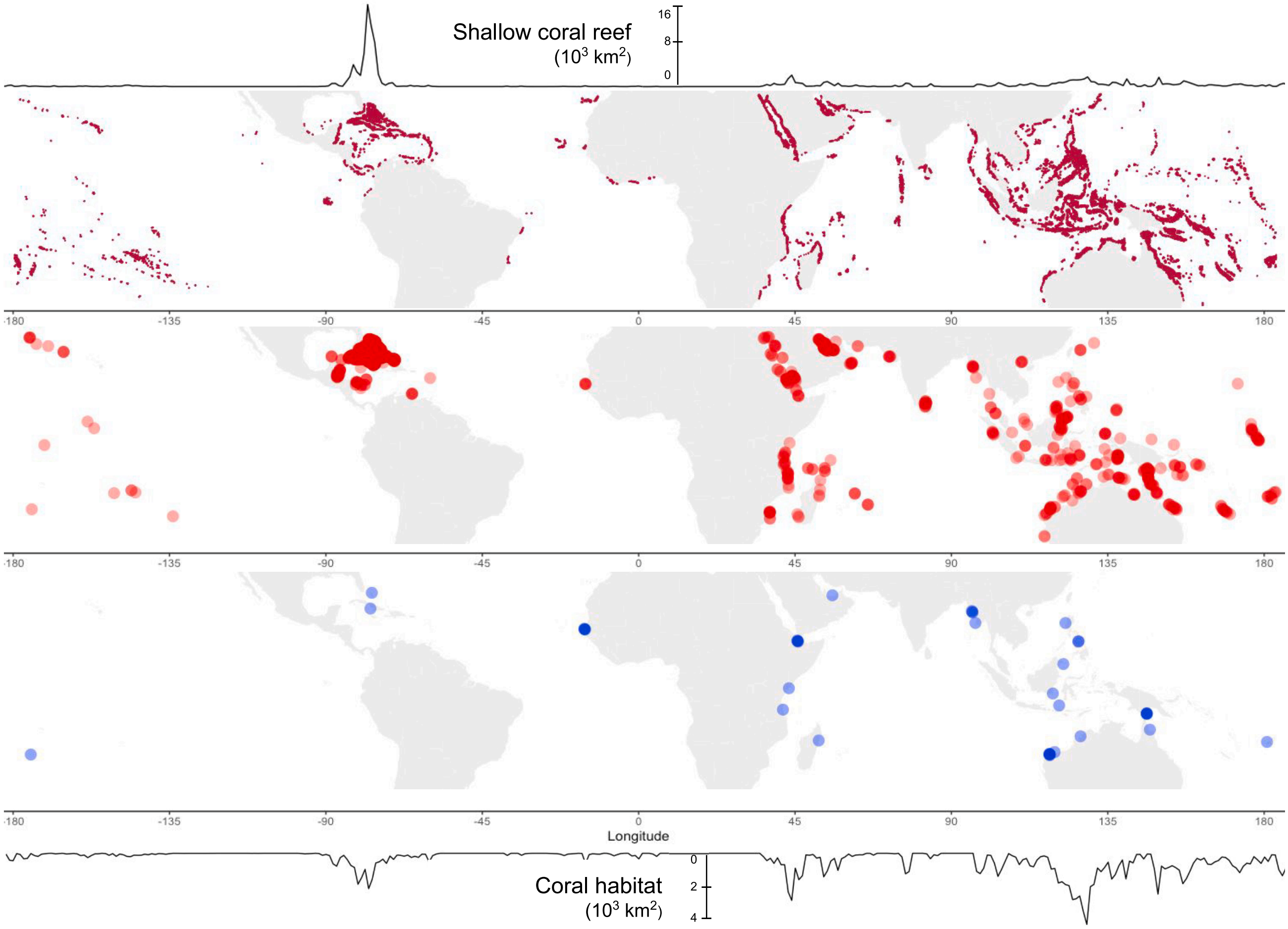

Figure 2. The distribution of the world's shallow coral reefs

The top map panel (maroon) shows the extent of all shallow coral reef areas mapped in this study and the associated top graph shows the longitudinal distribution of the area of shallow coral reefs. The graph under the bottom panel shows the longitudinal distribution of coral habitat (hard substrate coral habitat, see Box 1 for definitions). The second map panel (red) shows shallow coral reef hotspots, defined as individual 0.1° (approximately 11 × 11 km) grid cells with >45 km^2 of shallow coral reef area. The third map panel (blue) shows global coral habitat hotspots, defined as individual 0.1° grid cells with >45 km^2 of coral habitat. The cells are displayed on the map with transparency, so darker colors indicate multiple hotspots in the same location.

Philippines but only 19% as much coral habitat (Table 1). The Bahamas are dominated by huge expanses of soft sediment habitats (sand and seagrass, see map classification) that contain very little coral, whereas the Philippines are dominated by hard-bottom types (rock and coral/algae, see map classification). We mapped 26,371 km^2 (20,677–39,678 km^2, 95% confidence interval) of seagrass in the Bahamas, the largest area of seagrass within the coral reef ecosystems, which was recently shown to be the largest seagrass ecosystem on the planet.[38] These regional differences are critical, and globally consistent benthic substrate mapping will be able to drive comparisons and prioritizations for any reef region or jurisdiction.

Conservation and sustainability

A review of the scientific literature utilizing the previously largest coral reef mapping effort[13] found that four topics dominated the use cases: "visualization and inventories," "conservation planning," "fishery resources," and "connectivity modeling." Having globally consistent information at increased spatial and thematic resolutions is the first step toward commensurate increases in the capacity of those key management and conservation applications. Under major biodiversity initiatives, such as the Convention on Biological Diversity, multiple coastal and ocean ecosystems (mangroves, saltmarshes, coral reef, seagrass, macroalgae, and intertidal habitats) are listed together as headline indicators in the post-2020 biodiversity framework.[39] Globally consistent, publicly available maps will aid these initiatives by complementing existing mapping resources as well as providing baseline information in jurisdictions that lack resources to produce their own maps.[40] The maps and associated products we describe here have thus had immediate impact in a range of fields.

We envisage that individual regions will be integrated into management- and conservation-driven ecosystem frameworks, such as the Global Change Taxonomy and Living Earth,[41,42] the IUCN Redlist of Ecosystems,[36] and the Global Ecosystem

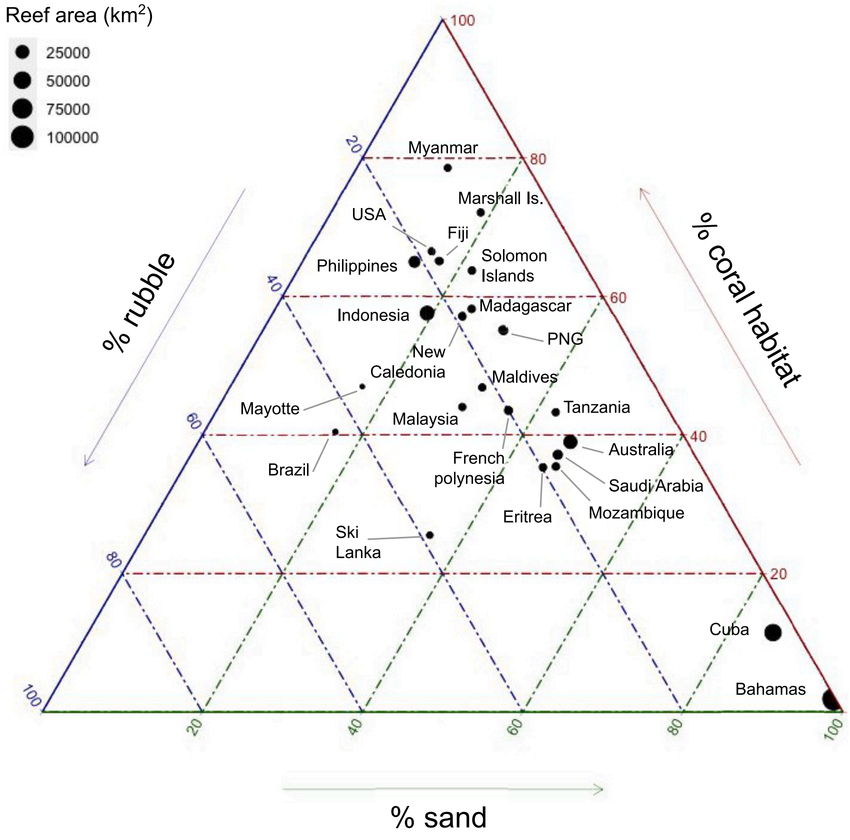

Figure 3. Benthic substrate composition of the world's largest coral habitat areas

Ternary plot for the top 20 jurisdictions ranked by area of coral habitat (as per Table 1). The ternary plots visualize benthic substrates by plotting the jurisdictions according to their relative percentage (of total area) of three core benthic substrate types: coral/hard substrate (coral/algae + rock), rubble, and sand. Several additional small reef areas (Brazil, Sri Lanka, Mayotte) have also been plotted to demonstrate higher rubble composition (~40% rubble).

Typology.[43] Taking the Global Ecosystem Typology as an example, there are several functional groups that could be assigned to classes within our shallow coral reefs area: seagrass meadows (M1.1), photic coral reefs (M1.3), subtidal rocky reefs (M1.6), subtidal sand beds (M1.7), and subtidal mud plains (M1.8). Some are globally consistent (e.g., seagrass meadows) but some would require regional remapping. Using our earlier example from the Bahamas, our sand benthic substrate class (see map classification) would map to subtidal sandbeds (M1.7) and our coral/algae class (see map classification) would map to photic coral reefs (M1.3); but, for the Great Barrier Reef in Australia, almost all benthic substrate classes (sand, rubble, rock, coral/algae, and microalgal mats; see map classification) would map to photic coral reefs (M1.3). The ability to consistently categorize coral reefs within frameworks like the Global Ecosystem Typology will be critically important for future reporting and conservation target initiatives and should be seen as a priority.

Real world impact

Via the Allen Coral Atlas, our new map products reached over 80,000 marine professionals in 2022 and around 60,000 in 2021, including marine and coastal managers, non-government organizations, and researchers. The Allen Coral Atlas web portal has about 14,000 return users (those that come back multiple times). Since its release in late 2021, the work prescribed in this paper has been directly cited in over 50 research papers, highlighting its growing impact and relevance. Use cases range from marine spatial planning, creating new marine protected areas, natural capital valuation, environmental assessments, restoration, education, ridge to reef projects, and state evaluation of coral reef species.[44–48] The data and tools are used to inform and improve policy, regulation, monitoring, and adaptation to climate change.[49–52] Researchers are using the data to develop artificial intelligence algorithms to measure reef halos,[53] analyze regional-scale fish community data and reef connectivity,[54] analyze global benthic complexity,[55] and uncover the impact of global-scale biogeographical and evolutionary histories on coral reef habitats.[56]

Non-government practitioners are using the data to support conservation efforts, restore corals, and identify environmentally sensitive areas, and we highlight a few examples here. The Nairobi Convention and Swedish Government collaborated to develop a marine spatial planning tool for the western Indian Ocean.[57] Using multiple input datasets, including the coral reef maps described in this paper, the tool quantifies ecosystems and environmental pressures, providing data that informs the regional marine spatial plan. Various other marine spatial planning projects and tools incorporating the coral reefs maps from the Allen Coral Atlas are in progress in Indonesia, Timor and Arafura Seas, Fiji, Solomon Islands, Tonga, Vanuatu, Panama, Belize, Bay of Bengal (including Bangladesh, India, Maldives, and Sri Lanka), Kenya, Australia, and western Micronesia.[58]

An example of the impact of the resolution of our new maps can be seen in the Blue Bonds[59] work by the Nature Conservancy in the Seychelles. This project downscaled a global analysis of the value of coral reefs to tourism[8] using a combination of global and local data sources of which the benthic substrate map presented here provided the baseline habitat data upon which the analysis was performed. The final map shows the distribution of on-reef spending and visitation across Seychelles' exclusive economic zone (EEZ), supporting policy to better plan and manage both the tourism industry and other active sectors in the blue economy.[60]

In the Pacific, tropical cyclones pose significant risks to both coral reefs and communities. The Vanuatu government,

Box 1. Definitions for the coral reef mapping area statistics reported in this paper

Shallow coral reefs: the amalgamation of all classes from the geomorphic zones map, which are mapped down to about 15 m water depth globally; this equates to any hard (coral, rock) or soft (sand, rubble, mud, seagrass) bottom substrate in the tropics able to be assigned a reef geomorphic zone; coral may or may not be present, and the underlying geomorphology is not always a coral-derived structure.

Coral habitat: the amalgamation of the rock and coral/algae classes from the dominant benthic substrate map, which is mapped down to about 10 m globally; this equates to a predominantly hard substrate, where most corals are growing and recruiting successfully; the coral/algae class includes areas covered >1% by coral and/or algae (carbonate or otherwise)—the class is combined because coral and algae are usually unable to be separated by multispectral satellite imagery; see map classification for class definitions.

Visible reef extent: a data fusion approach (see global visible reef extent mapping methods) that extends shallow tropical coral reefs into adjacent areas that were otherwise too deep or turbid to confidently assign a geomorphic zone or dominant benthic substrate class; includes areas down to a maximum of about 30 m deep, though this is not globally consistent due to water optical properties; it is intended for applications that require a more generalized and inclusive depiction of global reef extent.

supported by IUCN Oceania and other stakeholders, developed a Post Disaster Needs Assessment based on a range of socioeconomic and oceanographic datasets, including the Allen Coral Atlas benthic and geomorphic data as the underlying coral reef habitat information.[61] The outcomes included prioritization for restoration efforts, based on protection provided by the reef. Similarly, a Post Disaster Risk Assessment in Fiji for tropical cyclone Winston[62] recommends coral reef maps as a critical data source to identify coral rehabilitation areas, and our new maps were used to update these areas in 2021. These are just a few examples of how freely available and globally consistent habitat map resources can contribute to the management and prioritization of coral reef ecosystems and well-being for coastal people.

Repeatability and transparency of the mapping framework

Previous global-scale coral reef map products (WCMCv4,[15] Millennium[13,27]) necessarily used human-intensive methods that are difficult to repeat at regular intervals. Data freshness is increasingly influencing uncertainty in ecology and conservation applications,[63] driving methods with increased transparency and repeatability. More regular mapping naturally increases the chances of detecting environmental change but, importantly, it enables two more advantages: the ability to incorporate user feedback in a timely manner and the ability to capitalize on new technology and methods.

Version 1.0 of the Allen Coral Atlas was completed in 2021, and the repeatable framework allowed a full revision to version 2.0 in 2022.[64] We used an online participatory process via SeaSketch[65] to engage with over 90 local experts and users to identify both local-scale misclassifications and broad-scale systematic errors, which resulted in significant changes for version 2.0. We integrated new datasets (see global visible reef extent mapping methods) and improved mapping techniques—particularly in deeper water and poorer water quality areas—which resulted in an extra 90,000 km^2 of shallow reef area being assigned geomorphic and benthic classes in version 2.0. The version 2.0 update was focused on improving the baseline maps, and future efforts—likely at local to regional scales—will use these baselines for monitoring changes in benthic substrates over time.

Caveats and limitations

As with any map product, there are important caveats on the use and interpretation of the maps and statistics presented. Mapping accuracy and individual class error varied among regions (see validation and confidence intervals). We include confidence intervals around the area estimates of our mapping classes, which are critical for downstream applications but are missing from current global-scale coral reef maps. To maintain global consistency, we limited our geomorphic and benthic mapping to 15 m water depth and excluded highly turbid waters—identified by manually masking out areas where the benthic substrate could not be identified visually by interpreters. These areas are where errors of commission and omission increase sharply due to signal attenuation and interference. Thus, our estimates may be conservative due to not mapping in deep (>15 m) and turbid waters, most likely affecting the coral habitat estimates. Conversely, in areas that often have very clear water, the geomorphic and benthic maps may extend below the 15-m depth range if the bathymetry product is incorrect. Our maps broadly agree with the distribution as per the current global spatial data standard for coral reef extent,[16] though there is much regional variation (see geomorphic and benthic mapping methods, Figures S1 and S2, and Table S1). Specific frameworks for how to use the maps, and what not to do with them, are also being developed as the user base increases.[22]

Downstream applications

Global maps at 5-m resolution provide a data source more akin to our understanding of coral reef environments based on field observations, compared with coarser previous mapping efforts.[66] We expect our new maps will not only enhance existing management and conservation activities but also propel a raft of new spatially explicit applications such as biological process modeling,[11,54] geophysical and geomorphic process modeling,[55,56,67] enhanced reef connectivity integration,[54,68] high-resolution conservation decision making,[18] and interactions with fine-scale spatial anthropogenic pressures/threats.[69]

Earth-observation-based monitoring systems are proven to be effective at reducing deforestation[70] and in highlighting areas where urgent attention is required. In coral reef environments, near-real-time coral bleaching monitoring systems are emerging, which typically need to be bounded to reduce the data and computational complexity of the analysis,[19,71] meaning that reef-extent-only products are not suitable. Our map data have solved this bounding problem for alert systems by enabling the alerts to target specific benthic substrate types in the system—the implementation of such a monitoring system can be seen in the Allen Coral Atlas.[19,71] Many bleaching products are

Table 1. Mapped area (km^2) for major coral reef jurisdictions of the world

Jurisdiction	Visible reef extent	Shallow coral reefs	Coral habitat	Coral habitat 95% confidence interval
Indonesia	43,139	32,310	14,173	7,930–19,695
Australia	37,422	28,233	9,416	4,815–13,364
Philippines	19,863	15,097	7,741	4,762–10,205
Cuba	52,476	51,510	3,536	2,538–4,709
Papua New Guinea	13,253	8,572	3,533	1,621–4,808
Fiji	7,610	5,368	2,661	1,270–3,355
Saudi Arabia	9,765	8,446	2,257	1,430–2,841
New Caledonia	6,346	4,551	1,885	900–2,377
Myanmar	3,028	2,439	1,721	914–2,252
Solomon Islands	6,013	3,512	1,703	782–2,318
Marshall Islands	3,238	2,543	1,662	850–2,200
Madagascar	3,949	3,465	1,508	1,123–1,715
Bahamas	108,973	107,449	1,504	1,079–2,002
Maldives	5,067	2,989	1,308	770–1,529
United States	3,046	2,772	1,183	849–1,575
Eritrea	4,451	3,459	1,103	699–1,389
Mozambique	4,027	3,666	1,052	784–1,197
Malaysia	3,844	2,859	1,041	553–1,362
French Polynesia	6,280	4,824	1,030	780–1,311
Tanzania	3,387	2,988	1,017	757–1,156

Shallow coral reef is the total area (km^2) of coral reef mapped to geomorphic class in this study, whereas visible reef extent is an extension of this area into surrounding deeper or turbid waters. Coral habitat is the area (km^2) of hard-bottom substrate mapped in this study, followed by its 95% confidence interval. Box 1 provides a more comprehensive definition. The table shows the top 20 jurisdictions (around 78% of the world's shallow coral reef) ordered by area of coral habitat; all jurisdictions, along with additional statistics, can be found in Table S1.

at coarse spatial grids (e.g., NOAA Coral Reef Watch 5 km product suite[72]), meaning that alert grid cells integrate temperature and anomalies over multiple habitat types. Our new maps are effective at estimating reef composition within those alert cells, offering an ability to tailor the parameterization of bleaching thresholds to different settings or developing alerts derived at a level smaller than grid cells. For example, elevating the bleaching risk level for lagoons due to higher water residence times.

Conclusions

Our global coral reef mapping framework has built on previous efforts and knowledge, providing for the first time a globally complete map of coral reef geomorphic zones and benthic substrates. The mapping framework is a step change in the way we utilize earth observation products for global mapping, delivering the first global habitat maps from a CubeSat constellation. The maps integrate multiple satellite sensors, derived modeling products, cloud-based machine learning and contextual editing, and global-scale cooperation for including user data and feedback. The mapping is transparent and repeatable at short timescales, with a full global revision being completed within a year of release. The maps are already being adopted from local to global scales for a range of science, management, and conservation applications. At a time when there is a deluge of global spatial datasets and their value for conservation is being questioned,[73] we hope to have demonstrated the value of a collaborative, transparent, and iterative framework. We show that local-scale knowledge and information are able to flow through to global-scale products and update our knowledge of the distribution of an iconic and irreplaceable marine ecosystem type.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

All resources are publicly available as per below, but any further information and requests for data should be directed to the lead contact, Mitchell Lyons (mitchell.lyons@gmail.com).

Materials availability

The maps from this study can be interactively explored and freely downloaded as vector files via the Allen Coral Atlas (https://allencoralatlas.org/ [19]) or accessed via the Google Earth Engine public catalog as a raster https://developers.google.com/earth-engine/datasets/catalog/ACA_reef_habitat_v2_0. The bathymetry data can also be downloaded via the Allen Coral Atlas along with a visual image mosaic, but the underlying Planet Dove data we used as the base for our mapping is commercial and hence not publicly accessible, though it is visible as a layer on the Allen Coral Atlas portal.

Data and code availability

The mapping code and processing routines are publicly available (github.com/CoralMapping/AllenCoralAtlas; https://doi.org/10.5281/zenodo.3714180), along with the reference data used to derive training and validation points used for the mapping (https://doi.org/10.6084/m9.figshare.c.5233847.v6). The master data export used for the analysis, along with the code, is also publicly available (https://github.com/mitchest/global-coral-reefs; https://zenodo.org/doi/10.5281/zenodo.10223785).

Box 2. Definitions for the mapping classes for the geomorphic zones map

Shallow lagoon: any fully- to semi-enclosed, sheltered, flat-bottomed, sediment-dominated lagoon area shallower than approximately 5 m

Deep lagoon: any sheltered broad body of water, fully- to semi-enclosed by reef, with a variable depth (but deeper than approximately 5 m and shallower than the surrounding ocean) and a soft bottom dominated by reef-derived sediment

Inner reef flat: a low-energy, sediment-dominated, horizontal to gently sloping platform behind the outer reef flat

Outer reef flat: adjacent to the seaward edge of the reef, outer reef flat is a leveled (near horizontal), broad, and shallow carbonate platform, displaying distinct wave-driven zonation

Terrestrial reef flat: a broad, flat, shallow-to-semi-exposed area fringing reef flat, found directly attached to land at one side; it is subject to freshwater run-off, nutrients, and sedimentation

Reef crest: a zone marking the boundary between the reef flat and the reef slope, generally shallow and characterized by highest wave energy absorbance

Reef slope: a submerged, sloping area extending seaward from the reef crest (or flat) toward the shelf break; windward-facing or any direction if no dominant prevailing wind or current exists

Sheltered reef slope: any submerged, sloping area extending into deep water but protected from strong directional prevailing wind or current, either by land or by opposing reef structures

Back reef slope: a complex, interior—often gently sloping—reef zone occurring behind the reef flat; of variable depth (but deeper than reef flat and more sloped), it is sheltered, sediment-dominated, and often punctuated by coral outcrops

Plateau: any deep, submerged (>approximately 5 m), hard-bottomed, horizontal to gently sloping (angle shallower than approximately 10°), seaward-facing reef platform

Geomorphic and benthic mapping methods

Overview

The geomorphic zones and dominant benthic substrate maps presented in this study were created over the period 2020–2022, using a number of pre-existing, published scientific frameworks. The underlying mapping framework[21] is flexible and scalable, based on multi-source earth observation and expert-driven datasets, and has been adapted to other large-scale coral reef mapping applications.[23] The framework has three main modules: (1) ingestion and stacking of the input data sources; (2) machine-learning-driven map classification; and (3) map refinement via object-based rules and manual contextual editing. The globe was split into 30 individual mapping regions (see Tables S2 and S3 for a list of regions) to facilitate region-specific data generation, feedback, mapping implementations, and ecologically targeted rule sets. The mapping framework was implemented on Google Earth Engine, a cloud-based processing platform that facilitates scalable visualization and processing of spatial datasets.[74] All of the Google Earth Engine code used to produce the maps for each individual region is available, along with access to input and output data products (see data and code availability section).

Earth observation input data

The underlying satellite imagery on which the mapping products were based was a multi-temporal image mosaic derived from the PlanetScope constellation of Dove satellites (i.e., analytical PlanetScope imagery, hereafter Planet Dove mosaic; https://developers.planet.com/docs/data/sr-basemaps/). 3.7-m spatial resolution images between 2018 and 2020 were filtered to low tide acquisitions (to allow better discrimination of the reef features) and used to generate a “best scene on top” mosaic at 5-m resolution for each mapping region (acquired directly from Planet Labs). Approximately 589,000 images were used to generate the mosaic globally.

Bathymetry is a critical environmental variable for mapping coral reefs. An automated global bathymetry mapping method[20] was used to generate the water depth data (relative bathymetry). Sentinel-2 (2A and 2B; 2018–2020; 10-m resolution; approximately 1.05 million scenes) was used as the default satellite image source for deriving the bathymetry data due to its high spatial and radiometric resolution and good signal to noise ratio. Sentinel-2 did not cover all the mapped coral reef areas, particularly in remote locations (e.g., Micronesia and Central South Pacific). Any area missing Sentinel-2 data was filled with bathymetry derived from an additional multi-temporal Planet Dove mosaic (2018–2020; various resolution images resampled to a 5-m-resolution basemap) filtered to high tide acquisitions (to maximize probability of water coverage over reefs; approximately 578,000 scenes). Other environmental and textural variables (such as slope, wave climate, gray level co-occurrence metrics, band ratios) were calculated and added to the covariate stack.[21] All input data layers were segmented into image “objects” as per previously described methods.[21]

Training and validation data

The training data used were points sampled from a set of reference data (polygons), which were developed specifically for each region via a standardized global protocol.[23] Briefly, the reference data creation process involves a segmentation of a series of subsets (20 × 20 km) of the Plant Dove mosaic, and then a distributed set of these segments undergo an expert manual labeling process as one of the geomorphic or benthic mapping classes, guided by field data (e.g., photo quadrats), depth, expert knowledge, and classification scheme.[22] The amount of reference data and its spatial distribution is determined by the representativeness in complexity and variation within the mapping region. Around 500,000 photo quadrats, across 480 field datasets, were gathered from around 400 individuals/organizations and utilized for this process. A full list of data attribution can be found here: https://allencoralatlas.org/attribution/. We did not impose an a priori importance or distribution on the map compositions, thus we sampled 2,000 training points for each mapping class.

Map classification

The initial geomorphic and benthic maps are produced via a machine learning image classification.[21] A random forest classifier was used to train a model that predicts either geomorphic zonation or benthic substrate type using the input data layers and training data at known locations. A new model was fit for each mapping region—the exact specification of the model and input variables used in each region can be found in the code for each mapping region (see materials availability and data and code availability), but the follow parameter set was generally used: (sample size = 2,000 per class, number of trees = 200–400, minimum leaf population = 5–10, variables per split = sqrt(k)). The model predictions were applied at a nominal 5-m resolution (pixel resolution of the base Planet Dove satellite image mosaics). The geomorphic map was classified using only the segmented input data layers to create an object-based map that reflects the broad-scale structure of geomorphic zonations. The benthic substrate map was classified using both segmented and pixel-based input data layers to include the contextual information in the segmented data but also to allow the benthic classification to vary at the 5-m-pixel scale, which you would expect for benthic substrate variability. A full explanation and rationale for this can be found in previously published work.[21] Specific model diagnostics are not reported as the raw random forest outputs are extensively modified in the subsequent map refinement procedure, meaning that the diagnostics would not relate to the final map products.

The geomorphic zonation mapping classes included deep water, shallow lagoon, deep lagoon, inner reef flat, outer reef flat, terrestrial reef flat, reef crest, reef slope, sheltered reef slope, back reef slope, and plateau (Box 2). The deep-water class was an internal mapping class not included in the map outputs. The benthic substrate classes included sand, rubble, rock, coral/algae, seagrass, and microalgal mats (Box 3). The mapping classes were based on previously published methods, where the classes were developed via a process that aimed to balance coral reef geomorphology, ecology, and biology within the framework of earth observation using visual satellite imagery. Brief definitions are provided here (Boxes 2 and 3) and more detailed descriptions of these classes can be found in Kennedy et al.[22] and on the Allen Coral Atlas portal.[19]

Box 3. Definitions for the mapping classes for the benthic substrate map

Sand: any soft-bottom area dominated by fine unconsolidated sediments

Rubble: any habitat featuring loose, rough fragments of broken reef material

Rock: any exposed hard-bottom area with uncommon-to-scarce corals and fleshy macroalgae—it encompasses limestone reef matrix but also underlying non-reefal bedrock and "beach rock"

Coral/algae: any hard-bottom area supporting living coral and/or algae

Seagrass: any habitat where seagrass is the dominant biota

Microalgal mats: visible accumulations of microscopic algae in sandy sediments

Map refinement

The raw machine learning classification outputs were subject to a suite of contextual editing procedures, customized for each mapping region, which involved "object-based" rule sets as well as simple manual editing approaches. The object-based rules aim to correct misclassifications based on logical or contextual translations of geomorphological/ecological principles, which have been well described for coral reef applications.[18,21,23] An example for the geomorphic map would be that a small group of pixels classified as "reef crest" surrounded by a large area of inner reef flat would be reclassified as "inner reef flat" (reef crest must occur on the edge of the reef flat). An example for the benthic map would be if "seagrass" was classified where the geomorphic map indicated reef slope it would be reclassified as "coral/algae" (seagrass is very unlikely to occur on reef slope but is often confused with coral and algae due to similarly low spectral reflectance). Some manual editing was also used for the map products to mask out errors like image noise/artifacts in deep or turbid water, or rectify a misclassification problem that occurs over a very large extent. The latter was achieved by manually delineating polygons within which a rule was applied (e.g., all "reef crest" reclassified to "outer reef flat" to rectify an error where reef crest was mapped within a lagoonal area). Often these manual rules are directly informed by local or expert feedback. Because the bathymetry products were not scaled to absolute depth, each region also required a manual tuning of the bathymetry threshold to best estimate a 15-m contour. All of the object-based rules and manual editing geometries/rules are explicitly defined in the code for each mapping region (see materials availability and data and code availability). Figure S3 shows the result of applying the map refinement module to the raw machine learning classification outputs. The map output after this refinement stage is the final product and the map on which the validation and accuracy assessment was performed.

Global visible reef extent mapping methods

Despite the same mapping approach being applied globally, each mapping region still displayed some inconsistencies due to factors mainly attributable to water quality, image availability, field data availability, non-absolute bathymetry data, and inherent differences in reef type and structure. To standardize these differences in the context of global consistency, we used a data fusion approach to develop a global visible reef extent mask within which mapping was constrained. The reef extent mask was produced at 5-m-pixel resolution to match the habitat mapping, combining data from two additional sources: (1) a global reef extent product developed in parallel with the maps in this study[26] and (2) the global bathymetry data from this study. This process generally masked out reef classes toward the deeper limit of 15 m bathymetry constraint in this study that were less likely to meet a globally consistent definition of the geomorphic and benthic classes. Most commonly, this reduced the extent of the mapping where the geomorphic zones were mapped as one of the reef slope classes or plateaus.

The mask was applied identically to both the geomorphic and benthic map, and an example of the process can be seen in Figure S3. The final geomorphic mapping extent was then combined with the global extent mask, holes <400 pixels (0.64 Ha) were filled in and a 5-pixel (25 m) morphological filter (circle) was applied to smooth reef boundaries and regain missing slope/beach features. The final visible reef extent is the Allen Coral Atlas "reef extent" product. The data provided in the Google Earth Engine catalog (see materials availability and data and code availability) includes the reef extent product as one of the raster bands. Future versions of the Allen Coral Atlas portal may change, but the v2.0 data on Google Earth Engine will always replicate the statistics in this paper.

Validation and confidence intervals

At the time training data were sampled from the reference data polygons, a spatially independent set of validation data points was also sampled for each region. These points were held out for the accuracy assessment of the final products after the map refinement, calculating mapping error and generating confidence intervals for each of the mapping classes. Although the validation dataset contained around 2,000 points per class per region, for the purposes of this paper, we further randomly sub-sampled the full set. This was done to reduce the likelihood of spatial autocorrelation in the validation data and to reduce the tendency for very large samples to shrink confidence intervals.[75] Overall, we used around 78,000 points for the geomorphic validation and around 57,000 points for the benthic validation. Because the amount of reference data created for each region varied, the size of the validation dataset for each region also varied.

We calculated standard mapping accuracy metrics (overall accuracy, commission error, and omission error) and their confidence intervals using a nonparametric resampling approach.[75] Confidence intervals are an integral component of interpreting remote sensing products and are essential for generating meaningful error bounds when reporting area statistics from maps.[75,76] We used a resampling approach based on a nonparametric Monte Carlo procedure that has been shown to be useful for random forest-based remote sensing methods,[75] and large-scale coastal mapping frameworks, including coral reefs[21] and intertidal ecosystems.[33] The set of accuracy metrics (overall accuracy, omission error, commission error) for each region, for each of the geomorphic and benthic maps, were calculated by Monte Carlo resampling (random 66% split) the validation dataset with 1,000 iterations. The reported metric was taken as the mean of the sampling distribution and the 95% confidence interval was taken as the corresponding percentiles (i.e., 2.5th and 97.5th).

Unlike traditional approaches, there is no constraint for these intervals to be symmetric around the estimate. This results in a more useful representation of error because there is no expectation in reality that uncertainty would be symmetrical. These properties also provide useful (and non-symmetrical) estimates of the error bounds on the area reporting for individual classes. This is especially true because of the uneven distribution of error in terms of commission and omission (Tables S2 and S3). To calculate the 95% upper and lower bounds of class-based area estimates, we used the 95% confidence interval on the resampling distribution of omission/commission error. The bounds can be represented as:

$$\text{area}_{ij}\ 95\%\ \text{CI}_{\text{lower}} = \text{area}_{ij} - (\text{area}_{ij} * \text{commission}_{ij}\ P_{95})$$

$$\text{area}_{ij}\ 95\%\ \text{CI}_{\text{upper}} = \text{area}_{ij} + (\text{area}_{ij} * \text{omission}_{ij}\ P_{95})$$

where $area_i$ is the value of the mapped area of any of the individual geomorphic or benthic classes and P_{95} is the 95% percentile of the sampling distribution for the omission or commission error of class i and region j (or mean of all regions for global totals). The confidence intervals are naturally uneven compared with the mapping estimate, but this enables both a realistic and useful interpretation map-based area reporting for users, given that we are aware of the variation in omission and commission errors.

Across the 30 mapping regions, the average overall accuracy of the geomorphic zonation map was 69% (min: 46%, max: 89%), and for the benthic substrate map it was 66% (min: 49%, max: 80%). The overall accuracy and commission/omission error for each mapping region, along with confidence intervals, can be found in supplemental information (Tables S2 and S3). We also provide an error matrix generated from the validation set comprising all regions for the global geomorphic and benthic maps (Tables S4 and S5). All of the code and data required to run the accuracy assessment procedure is also provided (see materials availability and data and code availability).

Analysis and map statistics

In order to facilitate global reef area reporting for this paper, we created a grid of 0.1° × 0.1° grids, and exported the area of each mapping class within each grid at a resolution of 5 m, using the corresponding UTM (Universal Transverse Mercator) zone projection directly from Google Earth Engine. This enabled a more wieldy data source for calculating statistics as well as joining with other ancillary datasets.We use the WCMCv4 spatial layer—the current global standard for spatial extent of coral reefs (WCMCv4[16])—for comparison in this paper to both uncover differences as well as to serve as a pseudo-validation to identify potential gross errors. To ensure a consistent area calculation method, we imported the WCMCv4 spatial layer into Google Earth Engine and exported its extent area statistics in the same fashion as for the map classes within the studies mapping domain. In general, our maps have a similar area distribution to the WCMCv4 layer, though there is much regional variation due to the various thematic and spatial resolutions of the input datasets that comprise the WCMCv4 layer (Figures S1 and S2; Table S1).

In order to assign reef area statistics to individual jurisdictions, we assigned a jurisdiction to each global grid cell by intersection with a global layer that represents the combined extents of the world's countries and EEZs.[77] We use the term "jurisdictions" because the combined country and EEZ data may not always encompass an entire country's claim.

Note that users using the vector files downloaded from Allen Coral Atlas may encounter different area reporting due to the process of converting the map rasters to vector format and, additionally, those vector products will not have the global reef extent mask applied. Original raster versions can be accessed via Google Earth Engine (see materials availability and data and code availability).

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.crsus.2024.100015.

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AUTHOR CONTRIBUTIONS

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The authors declare no competing interests.

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REFERENCES

1. GCRMN (2020). Status of Coral Reefs of the World: 2020. Report of the Global Coral Reef Monitoring Network, October 5, 2021, D. Souter, S. Planes, J. Wicquart, M. Logan, D. Obura, and F. Staub, eds. https://www.unep.org/resources/status-coral-reefs-world-2020.
2. Morrison, T.H., Hughes, T.P., Adger, W.N., Brown, K., Barnett, J., and Lemos, M.C. (2019). Save reefs to rescue all ecosystems. Nature *573*, 333–336.
3. Moberg, F., and Folke, C. (1999). Ecological goods and services of coral reef ecosystems. Ecol. Econ. *29*, 215–233.
4. Bellwood, D.R., Hughes, T.P., Folke, C., and Nyström, M. (2004). Confronting the coral reef crisis. Nature *429*, 827–833.
5. Bayraktarov, E., Stewart-Sinclair, P.J., Brisbane, S., Boström-Einarsson, L., Saunders, M.I., Lovelock, C.E., Possingham, H.P., Mumby, P.J., and Wilson, K.A. (2019). Motivations, success, and cost of coral reef restoration. Restor. Ecol. *27*, 981–991.
6. Eddy, T.D., Lam, V.W.Y., Reygondeau, G., Cisneros-Montemayor, A.M., Greer, K., Palomares, M.L.D., Bruno, J.F., Ota, Y., and Cheung, W.W.L. (2021). Global decline in capacity of coral reefs to provide ecosystem services. One Earth *4*, 1278–1285.
7. Beck, M.W., Losada, I.J., Menéndez, P., Reguero, B.G., Díaz-Simal, P., and Fernández, F. (2018). The global flood protection savings provided by coral reefs. Nat. Commun. *9*, 2186.
8. Spalding, M., Burke, L., Wood, S.A., Ashpole, J., Hutchison, J., and zu Ermgassen, P. (2017). Mapping the global value and distribution of coral reef tourism. Mar. Policy *82*, 104–113.
9. Edgar, G.J., Stuart-Smith, R.D., Willis, T.J., Kininmonth, S., Baker, S.C., Banks, S., Barrett, N.S., Becerro, M.A., Bernard, A.T.F., Berkhout, J., et al. (2014). Global conservation outcomes depend on marine protected areas with five key features. Nature *506*, 216–220.
10. Graham, N.A.J., Jennings, S., MacNeil, M.A., Mouillot, D., and Wilson, S.K. (2015). Predicting climate-driven regime shifts versus rebound potential in coral reefs. Nature *518*, 94–97.
11. Dietzel, A., Bode, M., Connolly, S.R., and Hughes, T.P. (2021). The population sizes and global extinction risk of reef-building coral species at biogeographic scales. Nat. Ecol. Evol. *5*, 663–669.
12. Cinner, J.E., Huchery, C., MacNeil, M.A., Graham, N.A.J., McClanahan, T.R., Maina, J., Maire, E., Kittinger, J.N., Hicks, C.C., Mora, C., et al. (2016). Bright spots among the world's coral reefs. Nature *535*, 416–419.
13. Andréfouët, S., and Bionaz, O. (2021). Lessons from a global remote sensing mapping project. A review of the impact of the Millennium Coral Reef Mapping Project for science and management. Sci. Total Environ. *776*, 145987.
14. Hochberg, E.J., and Gierach, M.M. (2021). Missing the Reef for the Corals: Unexpected Trends Between Coral Reef Condition and the Environment at the Ecosystem Scale. Front. Mar. Sci. *8*, 727038.
15. Spalding, M., Ravilious, C., and Green, E.P.; United Nations Environment Programme (2001). World Atlas of Coral Reefs (University of California Press).
16. UNEP; WCMC; WorldFish Centre; WRI; TNC. Global distribution of warm-water coral reefs. Compiled from multiple sources including the Millennium Coral Reef Mapping Project, 2021. https://doi.org/10.34892/t2wk-5t34. https://data.unep-wcmc.org/pdfs/1/WCMC_008_Global_Distribution_of_Coral_Reefs.pdf?1617121809

17. Purkis, S.J., Gleason, A.C.R., Purkis, C.R., Dempsey, A.C., Renaud, P.G., Faisal, M., Saul, S., and Kerr, J.M. (2019). High-resolution habitat and bathymetry maps for 65,000 sq. km of Earth's remotest coral reefs. Coral Reefs *38*, 467–488.
18. Schill, S.R., McNulty, V.P., Pollock, F.J., Lüthje, F., Li, J., Knapp, D.E., Kington, J.D., McDonald, T., Raber, G.T., Escovar-Fadul, X., et al. (2021). Regional High-Resolution Benthic Habitat Data from Planet Dove Imagery for Conservation Decision-Making and Marine Planning. Remote Sens. *13*, 4215.
19. Allen Coral Atlas Partnership (2022). Imagery, maps and monitoring of the world's tropical coral reefs (Zenodo). https://doi.org/10.5281/zenodo.3833242.
20. Li, J., Knapp, D.E., Lyons, M., Roelfsema, C., Phinn, S., Schill, S.R., and Asner, G.P. (2021). Automated Global Shallow Water Bathymetry Mapping Using Google Earth Engine. Remote Sens. *13*, 1469.
21. Lyons, M.B., Roelfsema, M.C., Kennedy, E.V., Kovacs, E.M., Borrego-Acevedo, R., Markey, K., Roe, M., Yuwono, D.M., Harris, D.L., Phinn, S.R., et al. (2020). Mapping the world's coral reefs using a global multiscale earth observation framework. Remote Sens. Ecol. Conserv. *6*, 557–568.
22. Kennedy, E.V., Roelfsema, C.M., Lyons, M.B., Kovacs, E.M., Borrego-Acevedo, R., Roe, M., Phinn, S.R., Larsen, K., Murray, N.J., Yuwono, D., et al. (2021). Reef Cover, a coral reef classification for global habitat mapping from remote sensing. Sci. Data *8*, 196.
23. Roelfsema, C.M., Lyons, M., Murray, N., Kovacs, E.M., Kennedy, E., Markey, K., Borrego-Acevedo, R., Ordoñez Alvarez, A., Say, C., Tudman, P., et al. (2021). Workflow for the generation of expert-derived training and validation data: A view to global scale habitat mapping. Front. Mar. Sci. *8*, 1–13.
24. Bruno, J.F., and Selig, E.R. (2007). Regional decline of coral cover in the Indo-Pacific: timing, extent, and subregional comparisons. PLoS One *2*, e711.
25. Burke, L., Reytar, K., Spalding, M., and Perry, A. (2011). Reefs at risk revisited (Washington, DC: World Resources Institute).
26. Li, J., Knapp, D.E., Fabina, N.S., Kennedy, E.V., Larsen, K., Lyons, M.B., Murray, N.J., Phinn, S.R., Roelfsema, C.M., and Asner, G.P. (2020). A global coral reef probability map generated using convolutional neural networks. Coral Reefs *39*, 1805–1815.
27. Andréfouët, S., Muller-Karger, F.E., Robinson, J.A., Kranenburg, C.J., Torres-Pulliza, D., Spraggins, S.A., and Murch, B. (2006). Global assessment of modern coral reef extent and diversity for regional science and management applications: a view from space. In Proceedings of the 10th International Coral Reef Symposium (Japanese Coral Reef Society Okinawa), pp. 1732–1745.
28. Kenyon, T.M., Doropoulos, C., Wolfe, K., Webb, G.E., Dove, S., Harris, D., and Mumby, P.J. (2023). Coral rubble dynamics in the Anthropocene and implications for reef recovery. Limnol. Oceanogr. *68*, 110–147.
29. Miller, E.C., Hayashi, K.T., Song, D., and Wiens, J.J. (2018). Explaining the ocean's richest biodiversity hotspot and global patterns of fish diversity. Proc. Biol. Sci. *285*, 20181314.
30. Wang, L., Diao, C., Xian, G., Yin, D., Lu, Y., Zou, S., and Erickson, T.A. (2020). A summary of the special issue on remote sensing of land change science with Google earth engine. Remote Sens. Environ. *248*, 112002.
31. Andrello, M., Darling, E.S., Wenger, A., Suárez-Castro, A.F., Gelfand, S., and Ahmadia, G.N. (2022). A global map of human pressures on tropical coral reefs. Conserv. Lett. *15*, e12858.
32. Bunting, P., Rosenqvist, A., Hilarides, L., Lucas, R.M., Thomas, N., Tadono, T., Worthington, T.A., Spalding, M., Murray, N.J., and Rebelo, L.-M. (2022). Global Mangrove Extent Change 1996–2020: Global Mangrove Watch Version 3.0. Remote Sens. *14*, 3657.
33. Murray, N.J., Phinn, S.R., DeWitt, M., Ferrari, R., Johnston, R., Lyons, M.B., Clinton, N., Thau, D., and Fuller, R.A. (2019). The global distribution and trajectory of tidal flats. Nature *565*, 222–225.
34. Murray, N.J., Worthington, T.A., Bunting, P., Duce, S., Hagger, V., Lovelock, C.E., Lucas, R., Saunders, M.I., Sheaves, M., Spalding, M., et al. (2022). High-resolution mapping of losses and gains of Earth's tidal wetlands. Science *376*, 744–749.
35. Murray, N.J., Keith, D.A., Bland, L.M., Ferrari, R., Lyons, M.B., Lucas, R., Pettorelli, N., and Nicholson, E. (2018). The role of satellite remote sensing in structured ecosystem risk assessments. Sci. Total Environ. *619–620*, 249–257.
36. Keith, D.A., Rodríguez, J.P., Rodríguez-Clark, K.M., Nicholson, E., Aapala, K., Alonso, A., Asmussen, M., Bachman, S., Basset, A., Barrow, E.G., et al. (2013). Scientific Foundations for an IUCN Red List of Ecosystems. PLoS One *8*, e62111.
37. Beyer, H.L., Kennedy, E.V., Beger, M., Chen, C.A., Cinner, J.E., Darling, E.S., Eakin, C.M., Gates, R.D., Heron, S.F., Knowlton, N., et al. (2018). Risk-sensitive planning for conserving coral reefs under rapid climate change. Conserv. Lett. *11*, e12587.
38. Gallagher, A.J., Brownscombe, J.W., Alsudairy, N.A., Casagrande, A.B., Fu, C., Harding, L., Harris, S.D., Hammerschlag, N., Howe, W., Huertas, A.D., et al. (2022). Tiger sharks support the characterization of the world's largest seagrass ecosystem. Nat. Commun. *13*, 6328.
39. UNEP; OPEN ENDED WORKING GROUP ON THE POST-2020 GLOBAL BIODIVERSITY FRAMEWORK. PROPOSED HEADLINE INDICATORS OF THE MONITORING FRAMEWORK FOR THE POST-2020 GLOBAL BIODIVERSITY FRAMEWORK. 2021. https://www.cbd.int/doc/c/f191/8db7/17c0a45b42a5a4fcd0bbbb8c/sbstta-24-l-10-en.pdf
40. Nicholson, E., Watermeyer, K.E., Rowland, J.A., Sato, C.F., Stevenson, S.L., Andrade, A., Brooks, T.M., Burgess, N.D., Cheng, S.-T., Grantham, H.S., et al. (2021). Scientific foundations for an ecosystem goal, milestones and indicators for the post-2020 global biodiversity framework. Nat. Ecol. Evol. *5*, 1338–1349.
41. Lucas, R.M., German, S., Metternicht, G., Schmidt, R.K., Owers, C.J., Prober, S.M., Richards, A.E., Tetreault-Campbell, S., Williams, K.J., Mueller, N., et al. (2022). A globally relevant change taxonomy and evidence-based change framework for land monitoring. Glob. Change Biol. *28*, 6293–6317.
42. Owers, C.J., Lucas, R.M., Clewley, D., Planque, C., Punalekar, S., Tissott, B., Chua, S.M.T., Bunting, P., Mueller, N., and Metternicht, G. (2021). Living Earth: Implementing national standardized land cover classification systems for Earth Observation in support of sustainable development. Big Earth Data *5*, 368–390.
43. Keith, D.A., Ferrer-Paris, J.R., Nicholson, E., Bishop, M.J., Polidoro, B.A., Ramirez-Llodra, E., Tozer, M.G., Nel, J.L., Mac Nally, R., Gregr, E.J., et al. (2022). A function-based typology for Earth's ecosystems. Nature *610*, 513–518.
44. Baird, M.E., Green, R., Lowe, R., Mongin, M., and Bougeot, E. (2020). Optimising cool-water injections to reduce thermal stress on coral reefs of the Great Barrier Reef. PLoS One *15*, e0239978.
45. McKenzie, L.J., Yoshida, R.L., Aini, J.W., Andréfouet, S., Colin, P.L., Cullen-Unsworth, L.C., Hughes, A.T., Payri, C.E., Rota, M., Shaw, C., et al. (2021). Seagrass ecosystems of the Pacific Island Countries and Territories: A global bright spot. Mar. Pollut. Bull. *167*, 112308.
46. Jones, G.P., Srinivasan, M., Galbraith, G.F., Berumen, M.L., and Planes, S. (2022). Saving Nemo: Extinction Risk, Conservation Status, and Effective Management Strategies for Anemonefishes. In Evolution, Development and Ecology of Anemonefishes, V. Laudet and T. Ravasi, eds. (CRC Press), p. 14.
47. Stoltenberg, L., Schulz, K.G., Lantz, C.A., Cyronak, T., and Eyre, B.D. (2021). Late Afternoon Seasonal Transition to Dissolution in a Coral Reef: An Early Warning of a Net Dissolving Ecosystem? Geophys. Res. Lett. *48*, e2020GL090811.
48. Razak, T.B., Boström-Einarsson, L., Alisa, C.A.G., Vida, R.T., and Lamont, T.A.C. (2022). Coral reef restoration in Indonesia: A review of policies and projects. Mar. Policy *137*, 104940.

49. Smallhorn-West, P.F., Gordon, S.E., Dempsey, A.C., Purkis, S.J., Malimali, S., Halafihi, T., Southgate, P.C., Bridge, T.C.L., Pressey, R.L., and Jones, G.P. (2021). Tongan socio-environmental spatial layers for marine ecosystem management. Pac. Conserv. Biol. *27*, 86–92.
50. Delevaux, J.M.S., and Stamoulis, K.A. (2022). Prioritizing forest management actions to benefit marine habitats in data-poor regions. Conserv. Biol. *36*, e13792.
51. Murray, N.J., Bunting, P., Canto, R.F., Hilarides, L., Kennedy, E.V., Lucas, R.M., Lyons, M.B., Navarro, A., Roelfsema, C.M., Rosenqvist, A., et al. (2022). coastTrain: A Global Reference Library for Coastal Ecosystems. Remote Sens. *14*, 5766.
52. Wen, W., Bambic, B., and White, A. (2020). Allen Coral Atlas for coral reef management in Indonesia: a brief review. https://doi.org/10.20935/AL4145.
53. Franceschini, S., Meier, A.C., Suan, A., Stokes, K., Roy, S., and Madin, E.M.P. (2023). A deep learning model for measuring coral reef halos globally from multispectral satellite imagery. Remote Sens. Environ. *292*, 113584.
54. Cumming, G.S., and Bellwood, D.R. (2023). Broad-scale analysis of fish community data suggests critical need to support regional connectivity of coral reefs. Ecol. Appl. *33*, e2849.
55. Li, J., and Asner, G.P. (2023). Global analysis of benthic complexity in shallow coral reefs. Environ. Res. Lett. *18*, 024038.
56. Lutzenkirchen, L.L., Duce, S.J., and Bellwood, D.R. (2023). The global biogeography of reef morphology. Glob. Ecol. Biogeogr. *32*, 1353–1364.
57. Agency for Marine and Water Management (2022). WIO Symphony – a tool for ecosystem-based marine spatial planning. https://www.havochvatten.se/wio-symphony.
58. Allen Coral Atlas. Accelerating impact in 2022: the latest Allen Coral Atlas Impact Report. https://allencoralatlas.org/blog/atlas-2022-impact-report/.
59. Thompson, B.S. (2022). Blue bonds for marine conservation and a sustainable ocean economy: Status, trends, and insights from green bonds. Mar. Policy *144*, 105219.
60. The Nature Conservancy. Evaluation of Ecosystem Goods and Services for Seychelles' Existing and Proposed Protected Area System – Seychelles MPAS ecosystem services final report. 2022. https://mapping-ocean-wealth-in-seychelles-tnc.hub.arcgis.com/documents/TNC::seychelles-mpas-ecosystem-services-final-report-20220413/explore.
61. Filipe Waqabitu N.V. POST-DISASTER NEEDS ASSESSMENT: TC HAROLD & COVID-19, VANUATU VOLUME A SUMMARY REPORT. 2020. https://sheltercluster.s3.eu-central-1.amazonaws.com/public/docs/draft_volume_a_tc_harold_and_covid-19_pdna_summary_report_compressed.pdf
62. Government of Fiji (2016). Fiji Post Disaster needs assessment: Tropical Cyclone Winston.
63. Murray, N.J., Kennedy, E.V., Álvarez-Romero, J.G., and Lyons, M.B. (2021). Data Freshness in Ecology and Conservation. Trends Ecol. Evol. *36*, 485–487.
64. Roelfsema, C., Lyons, M., Markey, K., Say, C., and Bambic, B. What went into the 2022 geomorphic and benthic map update? (Allen Coral Atlas Press). https://allencoralatlas.org/blog/geomorphic-and-benthic-maps-2022-update/.
65. Burnett, C.M. (2020). Incorporating the participatory process in the design of geospatial support tools: Lessons learned from SeaSketch. Environ. Modell. Software *127*, 104678.
66. Kunin, W.E. (1998). Extrapolating species abundance across spatial scales. Science *281*, 1513–1515.
67. Tebbett, S.B., Streit, R.P., and Bellwood, D.R. (2020). A 3D perspective on sediment accumulation in algal turfs: Implications of coral reef flattening. J. Ecol. *108*, 70–80.
68. Schill, S.R., Raber, G.T., Roberts, J.J., Treml, E.A., Brenner, J., and Halpin, P.N. (2015). No Reef Is an Island: Integrating Coral Reef Connectivity Data into the Design of Regional-Scale Marine Protected Area Networks. PLoS One *10*, e0144199.
69. Bellwood, D.R., Pratchett, M.S., Morrison, T.H., Gurney, G.G., Hughes, T.P., Álvarez-Romero, J.G., Day, J.C., Grantham, R., Grech, A., Hoey, A.S., et al. (2019). Coral reef conservation in the Anthropocene: Confronting spatial mismatches and prioritizing functions. Biol. Conserv. *236*, 604–615.
70. Moffette, F., Alix-Garcia, J., Shea, K., and Pickens, A.H. (2021). The impact of near-real-time deforestation alerts across the tropics. Nat. Clim. Chang. *11*, 172–178.
71. Li, J., Fabina, N.S., Knapp, D.E., and Asner, G.P. (2020). The Sensitivity of Multi-spectral Satellite Sensors to Benthic Habitat Change. Remote Sens. *12*, 532.
72. Skirving, W., Marsh, B., De La Cour, J., Liu, G., Harris, A., Maturi, E., Geiger, E., and Eakin, C.M. (2020). CoralTemp and the Coral Reef Watch Coral Bleaching Heat Stress Product Suite, Version 3.1. Remote Sens. *12*, 3856.
73. Wyborn, C., and Evans, M.C. (2021). Conservation needs to break free from global priority mapping. Nat. Ecol. Evol. *5*, 1322–1324.
74. Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., and Moore, R. (2017). Google Earth Engine: Planetary-scale geospatial analysis for everyone. Remote Sens. Environ. *202*, 18–27.
75. Lyons, M.B., Keith, D.A., Phinn, S.R., Mason, T.J., and Elith, J. (2018). A comparison of resampling methods for remote sensing classification and accuracy assessment. Remote Sens. Environ. *208*, 145–153.
76. Olofsson, P., Foody, G.M., Herold, M., Stehman, S.V., Woodcock, C.E., and Wulder, M.A. (2014). Good practices for estimating area and assessing accuracy of land change. Remote Sens. Environ. *148*, 42–57.
77. Flanders Marine Institute (2019). Maritime Boundaries Geodatabase, version 11. https://www.marineregions.org/downloads.php.