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A Global Systematic Literature Review of Ecosystem Services in Reef Environments

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Abstract

Ecosystem services (ES) embrace contributions of nature to human livelihood and well-being. Reef environments provide a range of ES with direct and indirect contributions to people. However, the health of reef environments is declining globally due to local and large-scale threats, affecting ES delivery in different ways. Mapping scientific knowledge and identifying research gaps on reefs' ES is critical to guide their management and conservation. We conducted a systematic assessment of peer-reviewed articles published between 2007 and 2022 to build an overview of ES research on reef environments. We analyzed the geographical distribution, reef types, approaches used to assess ES, and the potential drivers of change in ES delivery reported across these studies. Based on 115 articles, our results revealed that coral and oyster reefs are the most studied reef ecosystems. Cultural ES (e.g., subcategories recreation and tourism) was the most studied ES in high-income countries, while regulating and maintenance ES (e.g., subcategory life cycle maintenance) prevailed in low and middle-income countries. Research efforts on reef ES are biased toward the Global North, mainly North America and Oceania. Studies predominantly used observational approaches to assess ES, with a marked increase in the number of studies using statistical modeling during 2021 and 2022. The scale of studies was mostly local and regional, and the studies addressed mainly one or two subcategories of reefs' ES. Overexploitation, reef degradation, and pollution were the most commonly cited drivers affecting the delivery of provisioning, regulating and maintenance, and cultural ES. With increasing threats to reef environments, the growing demand for assessing the contributions to humans provided by reefs will benefit the projections on how these ES will be impacted by anthropogenic pressures. The incorporation of multiple and synergistic ecosystem mechanisms is paramount to providing a comprehensive ES assessment, and improving the understanding of functions, services, and benefits.

Keywords Ecosystem benefits · Marine ecosystem services · Reef systems · Coastal livelihoods · Human well-being · Food security

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Introduction

Human well-being and livelihood rely upon ecosystem goods and services. Yet, there is a growing concern that biodiversity change leads to erosion of nature's contribution to people (Díaz et al. 2006). The concept of ecosystem services (ES), defined as "components of nature, directly enjoyed, consumed, or used to yield human well-being", gained popularity after the Millennium Ecosystem Assessment program launched in 2001, and has impacted high-level policy goals and decisions worldwide (Reid 2005). For instance, data from ES assessments may inform landscape and urban planning, systematic conservation planning, environmental impact assessments, and strategic environmental evaluations (Baker et al. 2013). Moreover, practical applications using assessment approaches such as cost-benefit (Li et al. 2021) or multi-criteria analyzes (Langemeyer et al. 2016) allow for evaluating the effects of adaptive management options on ES delivery. Such approaches offer policy instruments that build a safe ground to manage the multiple benefits of ES (Schröter et al. 2019).

In marine and coastal ecosystems, reefs–habitats that develop into consolidated substrates (Sheppard et al. 2017) play a key role in providing services, contributions, and benefits that support human economy, livelihood, and well-being (Woodhead et al. 2019; Barbier et al. 2011). More than 625 million people live along the world's coastal zones (Neumann et al. 2015), and many rely directly or indirectly on the ES contributions from reef habitats (Spalding et al. 2017). Although coral reefs built by scleractinian corals have a central place in reef ES studies due to their tropical nature, high biodiversity and touristic value (Spalding et al. 2017; Santavy et al. 2021), other reef types may also deliver a range of ES. Such reef types include those formed by other biogenic organisms such as oysters and coralligenous algae, those formed by rocky substrates like rocky reefs, and human-made structures such as shipwrecks and intentionally sunk artificial reefs. Such reef environments have different characteristics of structural complexity, biodiversity of associated organisms, and resilience to stressors, although little is known about the ES they deliver. Nevertheless, in general, benefits supplied by reef environments to humans are diverse and include provisioning services such as food production (Robinson et al. 2022), pharmaceutical products (Albert et al. 2015), coastal protection (van Zanten et al. 2014), and cultural ES with recreational, touristic, aesthetic, spiritual, educational and scientific values (Spalding et al. 2017; Tribot et al. 2018; Friess et al. 2020).

Despite the multiple ES provided to humanity, reef environments are facing escalating anthropogenic pressures at different scales (Halpern et al. 2015; Magris et al. 2021). Globally, climate change and ocean acidification have threatened the persistence of tropical coral reefs (Hughes et al. 2017; Wilkinson 1999). Other local and regional anthropogenic drivers of change, such as overfishing, pollution, and biological invasions (He and Silliman 2019; Blowes et al. 2019; Fogliarini et al. 2021) are degrading considerable extensions of reef environments worldwide (McAfee and Connell 2021) and harming the ES they provide (Pendleton et al. 2016; Woodhead et al. 2019). Among them, coral reefs, the most biodiverse marine ecosystem and source of multiple forms of human use and benefits (Santavy et al. 2021) have lost half of their global area since 1950 (Eddy et al. 2021). Most losses in reef environments are sought to be irreversible in the face of anthropogenic climate change (Ponti et al. 2021), jeopardizing communities and livelihoods that depend on their associated ES. Nevertheless, the drivers of change in other reef types still need to be assessed once these reefs occur in different geographic, environmental and social settings when compared to coral reefs (Leão et al. 2016; Perry and Larcombe 2003; Kleypas et al. 1999).

Research on ES and their benefits has grown considerably in the last two decades (reviewed in Liquete et al. 2013; Milcu et al. 2013; Ruiz et al. 2021). However, marine and coastal ES have been poorly assessed when compared to terrestrial environments (Rodrigues et al. 2017), meaning that researchers still need to access a range of topics for a broader understanding of ES delivered by the sea. Fortunately, some recent studies have mapped priorities in the field (e.g., Rodrigues et al. 2017; Rivero and Villasante 2016). Among these priorities are topics linking ES with human well-being, and integrating economics, natural and social sciences into ES assessments (Rivero and Villasante 2016). Together, these topics comprise a permanent agenda for the United Nations Decade of Ocean Science for Sustainable Development (Intergovernmental Oceanographic Commission 2018) and have incentivized research during the last years. However, marine researchers still need a guide of available tools for assessing ES including already developed research topics and information on the global spatial distribution of ES research efforts.

Here, we present a semi-quantitative evaluation of the peer-reviewed literature produced worldwide assessing the ES in reef environments. We cover the following topics: (i) *Overview and general patterns*, showing trends of reef ES research, per reef type, and the approaches used; (ii) *Reef environments and ecosystem services: categories, subcategories, temporal and spatial attributes*, highlighting temporal and spatial research trends per type of ES assessed; and (iii) *Drivers of change in ecosystem services*, exploring the frequency in which different drivers of change in reef habitats were cited across studies. By providing this state-of-the-art of ES research on reef environments, we seek to map the knowledge in space and time, identify research gaps, and guide future research within the field.

Table 1 Attributes (variables) and methodological information extracted from each article in the literature reviewed. The full dataset is available in the supplementary material

Variable	Data type	Description	Units/levels
1- Study approach	Categorical	The main approach used to conduct the ES assessment	Experiment; Modeling; Observation; and Perception
2- Use of temporal data	Binary	If some type of temporal data was used in the analysis	Yes/no
3- Type of reef habitat	Categorical	Type of reef habitat where the study was conducted	Coral; Coralligenous; Rocky; Oyster; Artificial; other biogenic reefs
4- Scale	Categorical	The geographic scale of data used in ES assessment	Local (one specific location studied); Regional (multiple sites studied); National (country-wide sites studied); Continental/global (data from a continent, or global data)
5- Categories of ES	Categorical	The ES category assessed in the study, standardized following Liquete et al. (2013) framework	1) Provisioning; 2) Regulating and Maintenance; and 3) Cultural
6- Subcategories of ES	Categorical	The ES subcategory assessed in the study, standardized following Liquete et al. (2013) framework	1) Food provision; Water storage and provision; Biotic Materials and Fuels 2) Water purification; Air quality regulation; Coastal protection; Climate regulation; Weather regulation; Ocean nourishment; Life cycle maintenance; Biological regulation 3) Symbolic and aesthetic values; Recreation and tourism; Cognitive effects
7- Drivers of change in ES	Categorical	Current direct and/or potential drivers of change in ES	Pollution; Overexploitation; Reef degradation; Climate Change; Erosion/sedimentation; Aquaculture; Mining/dredging; Natural hazards; Invasive species; Unregulated tourism; Lack of management; and Socioeconomic shifts

Material and Methods

Data Collection—Literature Review

We performed a systematic literature review through the PRISMA protocol, using explicit eligibility criteria (Moher et al. 2009). The scientific literature was examined by searching on the Web of Science database (Clarivate Analytics) for peer-reviewed research articles using Boolean search terms, exclusively in English. The search key was verified in the title, abstract, and keywords through the terms: "ecosystem service*" OR "environmental service*" AND reef*. Using these keywords, we focused on studies explicitly rooted in the ecosystem service assessments in reef environments. The literature search was performed in May 2023 and included articles published between 2007 and 2022. Although there is information in reports, conference abstracts, and languages other than English, especially in regional journals, we believe that our sample is representative since most of the global literature is in English. We acknowledge that the articles found using these keywords may not retain every single paper that addressed reef ES because other terms may be used, such as economic valuation and cultural services. Nonetheless, the terms used here allowed us to have a broad overview of most of the published literature and to draw reliable conclusions about current approaches to ES research on reef environments.

Our literature search returned 998 articles. In the first screening, duplicates were removed, resulting in 929 articles. In a second screening, abstracts were assessed to verify if the article investigated ES in reef environments, resulting in a total of 229 articles being selected. Finally, in the eligibility phase, full-text articles were screened and retained based on the following criteria: (i) if they evaluated ES in natural or artificial reef environments, and (ii) if they used qualitative and/or quantitative approaches to assess such services (see the flowchart in Fig. S1). We excluded articles that (i) mentioned ES only in the introduction and/or discussion sections (i.e., describing the relevance of studied subjects), (ii) were purely methodological, and (iii) were literature reviews to avoid gathering duplicated data. The eligibility phase returned 115 articles, which were analyzed in depth in our review.

For each retained article, we extracted the article year, the country/countries where the study was conducted, and seven attributes related to the study approach, geographical distribution, and drivers of change in the delivery of ES to people (Table 1). Attributes were selected based on previous descriptive reviews on ES (Egoh et al. 2012; Milcu et al. 2013; Seppelt et al. 2011). In our review, ES were organized into categories and subcategories following the framework of Liquete et al. (2013) due to its adherence to marine and coastal ecosystems. For studies that applied different categorization schemes (e.g., Millennium Ecosystem Assessment, MEA 2005; and Common International Classification of Ecosystem Services, CICES, Haines-Young and Potschin 2011), we reclassified the services or benefits following the integrated classification of marine and coastal services proposed by Liquete et al. (2013).

Drivers of change in ES delivered to people were ascribed to 12 categories, broadly defined within direct impacts (e.g., mining, pollution and invasive species) and/or indirect impacts (e.g., lack of management and socioeconomic shifts). A driver of change was added to the review if it was

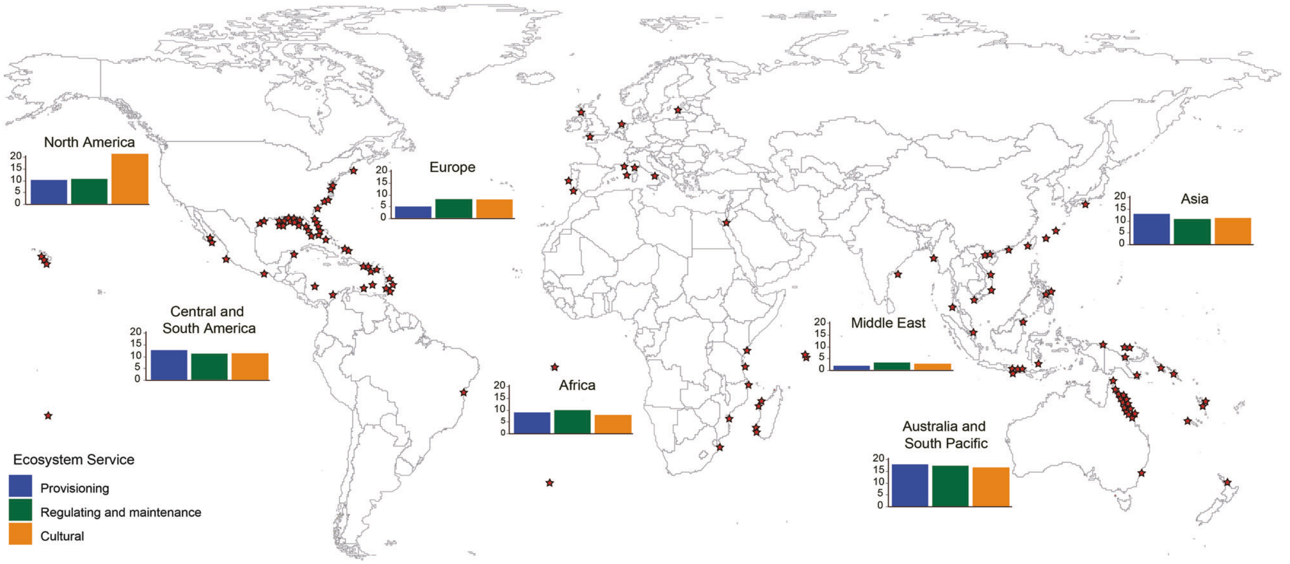

Fig. 1 Global distribution of studied sites assessed in the analyzed articles. Barplots represent the number of studies (y-axis) that assessed each category of ecosystem services (x-axis) in each region. Ecosystem services' categories followed the classification of Liquete et al. (2013). Studies that only used scales larger than the site (e.g., national and continental/global scale) were not included in the map

mentioned as influencing or threatening the surveyed ES. For instance, Marshall et al. (2019) investigated how people valued different ecosystems within the Great Barrier Reef and described that debris (plastic and bottles) were an important concern affecting the quality of reef ES for local users. Thus, we categorized this concern under the "Pollution" category.

Data Analysis

To explore the number of studies developed across different reef habitats and ES categories and subcategories, we plotted a Sankey diagram built using the Raw Graph data visualization tool (https://www.rawgraphs.io/). We also produced a global map of ES research, based on the number of studies per subject, by matching the identity of studied countries with countries in a world map using the R package *viridis* (Garnier et al. 2018). We used frequencies and percentages to evaluate how different types of ES (using the classification of Liquete et al. (2013)), approaches, scales, site characteristics, and reef habitat types were used across studies.

To evaluate drivers of change in ES categories and subcategories, we produced a heatmap with a hierarchical clustering grouping of drivers that were closely related to ES categories and subcategories. We measured the dissimilarity between drivers associated with ES categories/subcategories using Euclidean distance, and built a dendrogram through a complete-linkage clustering algorithm. The similarity matrix, dendrogram, and heatmap were built within the R environment v. 4.1.2 (R Core Team 2019) using the package *gplots* (Warnes et al. 2020).

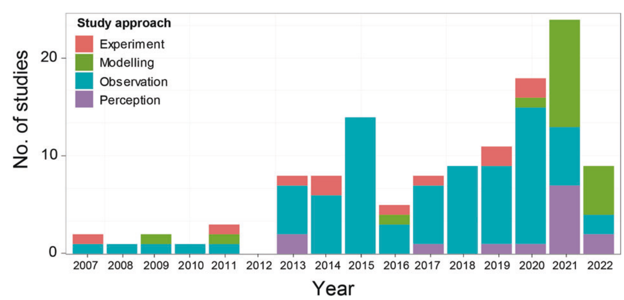

Fig. 2 Number of studies over the years according to the different study approaches (note that a study may be represented by more than one approach)

Results

Overview and General Patterns

The final screening of eligible studies resulted in 115 articles with publishing years varying from 2007 to 2022 (Table S1). The global coverage of studies showed a geographic bias towards North America (mainly the United States, 23.1% of the studies), and Oceania and South Pacific nations (mainly Australia, comprising 11.6% of the studies) (Fig. 1). Overall, the studied categories of ES were similar among geographic regions, except for North America, in which cultural ES represented twice the number of other studied categories (Fig. 1). The number of studies per year has increased since 2007, peaking in 2021 with 38 articles (Fig. 2). Studies were conducted mostly on coral reefs (63.8%), followed by oyster reefs (18.5%), and artificial

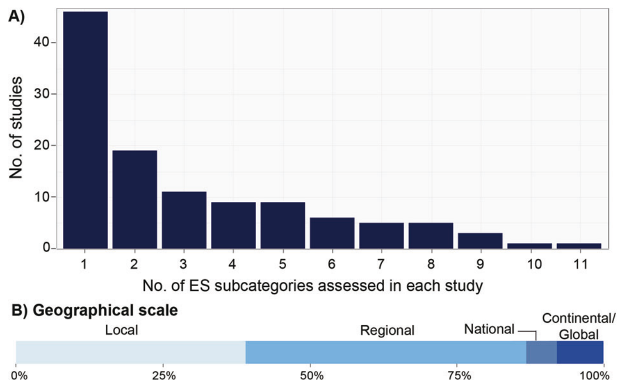

Fig. 3 **A** Number of subcategories of ecosystem services investigated in the analyzed studies. Ecosystem services' categories followed the classification of Liquete et al. (2013). **B** Percentage of studies fitting to different geographical scales of study

reefs (7.8%), with a small fraction assessing ES in rocky reefs (4.3%), coralligenous reefs (3.4%), and other types of biogenic reefs (2.6%). Four studies assessed ES in more than a single reef environment type. Marre et al. (2015) conducted a nationwide online survey to evaluate ES throughout the Australian coastal zone, assessing ES in all reef environments of the country (coral reefs, rocky reefs, artificial reefs and other biogenic reefs). Rees et al. (2015) combined spatial analysis with quantitative and qualitative survey methods to assess trends in cultural ES in temperate artificial and biogenic reefs in Lyme Bay, SW England. Simard et al. (2016) investigated cultural ES by counting boat visits in artificial and natural reefs in the Gulf of Mexico using acoustic recorders. Finally, Yang et al. (2019) used accounting techniques to evaluate ES in coral and rocky reefs of the Pearl River Delta, in China.

Researchers have evaluated ES in reef environments using observational approaches (61.9%), followed by statistical modeling (18.2%), perceptions from stakeholders (11.1%) and experiments (8.7%). Modeling approaches show a remarkable increase in the number of studies in 2021 and 2022, representing 80% of studies carried out so far (Fig. 2). Interestingly, the number of studies using observation approaches decreased 50% in 2021 and 2022 in relation to the previous five years.

Reef Environments and Ecosystem Services: Categories, Temporal and Spatial Attributes

Regulating and maintenance were the most assessed ES categories (39% of studies), followed by cultural (33.3%), and provisioning (27.6%) ES categories. Fifty-six percent of the studies assessed one or two ES subcategories (Fig. 3A), and the average number (±s.d.) of ES categories and subcategories assessed per study was 1.8 ± 0.9 and 3.1 ± 2.51, respectively. Sixty percent of the studies did not use temporal data to evaluate ES. Studies that assessed temporal trends on ES usually relied on short time series (<10 years) and were conducted from 2012 onwards. The spatial scale of studies was mostly local and regional, representing 87% of the total number of studies (Fig. 3B).

Among the assessed ES categories, regulating and maintenance comprised most of the evaluations for coral reef, rocky reef, artificial reef, and oyster reef (Fig. 4A–D). Concerning subcategories, the most assessed were those related to cultural (subcategory recreation and tourism, $n = 63$), provisioning (subcategory food provision, $n = 58$), and regulating and maintenance ES (subcategory life cycle maintenance, $n = 50$). Subcategories related to regulating and maintenance ES were more frequently assessed on oyster reefs, representing 66.7% of studies. Prevalent ES subcategories were water purification (22%) and life cycle maintenance (20%). The latter is related to the maintenance of key habitats that act as nurseries, spawning areas, or migratory routes. These habitats and their connectivity are essential to the life cycle of a variety of species (Liquete et al. 2013). Recreation and tourism (cultural ES) was the most studied ES subcategory in coral (20%), rocky (16%) and artificial reefs (26%).

Drivers of Change in Ecosystem Services

Sixty-seven percent of the studies attributed one or more drivers of change to the evaluated ES. The description of potential drivers of change was more frequent in studies addressing regulating and maintenance ES (42%), followed by cultural (36%) and provisioning ES (22%). Among the cited drivers of change, overexploitation, reef degradation and climate change were the most cited for provisioning ES (59%), impacting mainly the subcategory food provision (Fig. 5). For regulating and maintenance services, overexploitation, pollution and climate change were the most cited drivers affecting the delivery of ES, totaling 61% of the citations, and impacting mainly the subcategories life cycle maintenance and coastal protection. Among cultural ES, the main drivers of change were pollution, climate change and overexploitation (54%), affecting mainly the subcategory recreation and tourism. Drivers related to social issues (lack of management and socioeconomic shifts) were more cited for cultural (23%) and regulating and maintenance ES (17%) (Fig. 5). The hierarchical clustering (based on citation frequency of multiple drivers of ES change) revealed three main groups of drivers of change in ES. The first comprised the most mentioned driver of change (overexploitation). The second was linked with secondarily mentioned drivers and related to social context (socioeconomic shifts and lack of management) and anthropogenic impacts such as pollution, reef degradation and climate change. Finally, the third group was formed by the five less cited drivers, which were mostly directly related to human activities, in addition to natural hazards (Fig. 5).

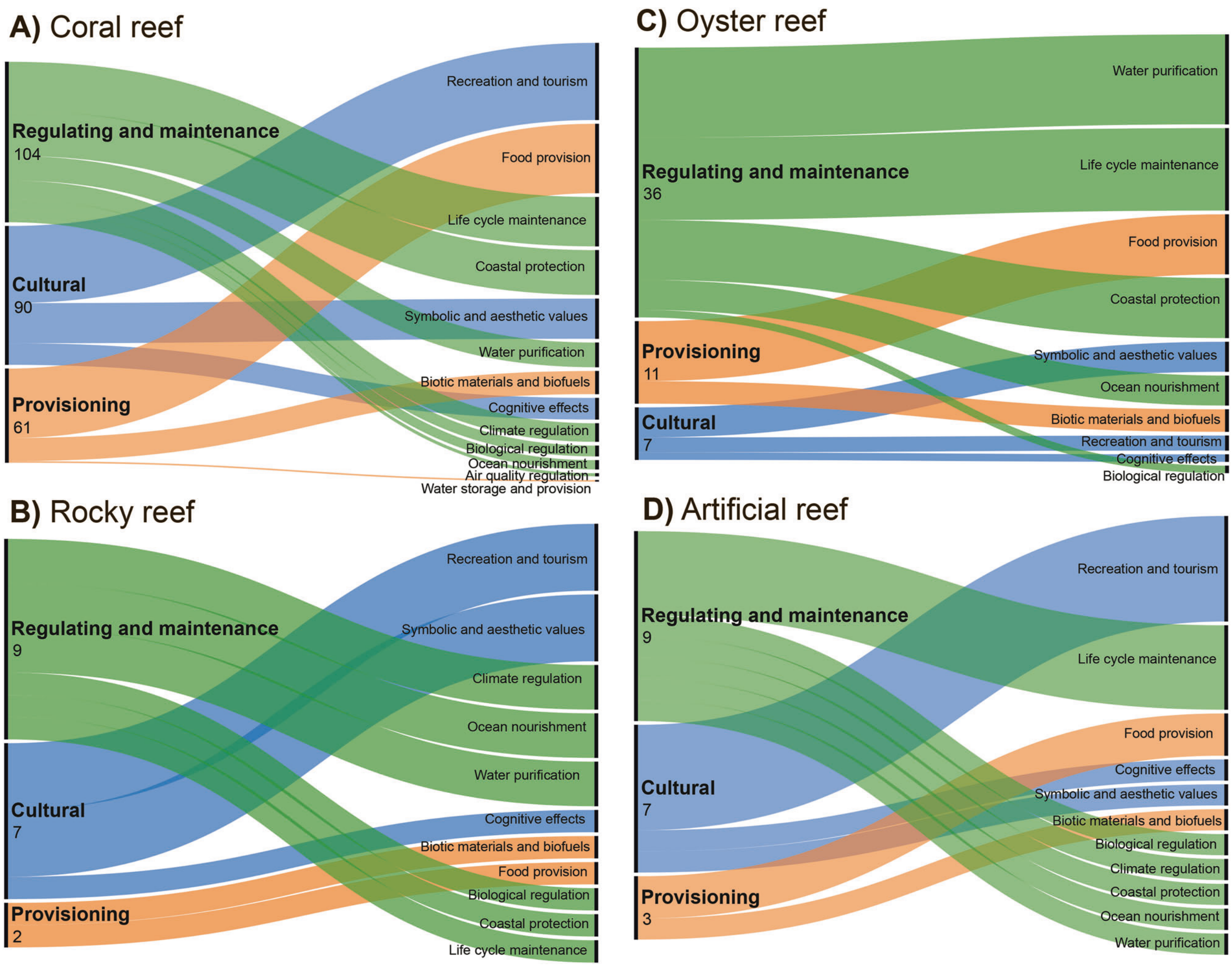

Fig. 4 Relationship among studied reef habitats (**A**) coral reefs; (**B**) rocky reefs; (**C**) oyster reefs; and (**D**) artificial reefs, and the categories (left column of each plot) and subcategories (right column of each plot) of ecosystem services evaluated. Ecosystem services' categories and subcategories followed the classification of Liquete et al. (2013). The height of each vertical colored line is related to number of citations of each specific habitat and ES category and subcategory in our dataset

Discussion

This study provides an overview of the research on ES in reef environments. Studies quantifying ES on reefs used mainly observational techniques. However, in the last two years statistical modeling approaches predominated, contributing with circa of half of the published articles. Such approaches have allowed researchers to project the effects of global changes on ES. For instance, Hafezi et al. (2021) used multilayered modeling approaches to develop an integrated assessment framework to evaluate coral reef health under different climate change scenarios, and, consequently their economic impacts in Vanuatu. On a wider scale, Burke and Spalding (2022) used high-resolution statistical models to generate high-resolution maps of shoreline protection by the world's coral reefs. Their study revealed that 26% of the coastline of the world's coral reef nations receive protection benefits. Such a marked increase in studies using modeling approaches may be a consequence of the COVID-19 pandemic since the lockdown constrained fieldwork in most regions and authors used databases to address reef ES through statistical modeling. Such modeling articles used mainly open-access databases of species occurrence (e.g., OBIS, GBIF), fisheries effort (Sea Around Us), environmental factors (BioOracle), and socioeconomic data to infer patterns in ES delivery (World Bank). Despite being a more recent subject in marine environments compared to terrestrial ones (Rodrigues et al. 2017), ES assessments in reef environments play an important role in the development and evolution of marine ES frameworks. In the last five years, we observed an increase in research using temporal and/or spatial databases of species occurrence and human use of species (e.g., Sato et al. 2020; Eddy et al. 2021), improving the understanding

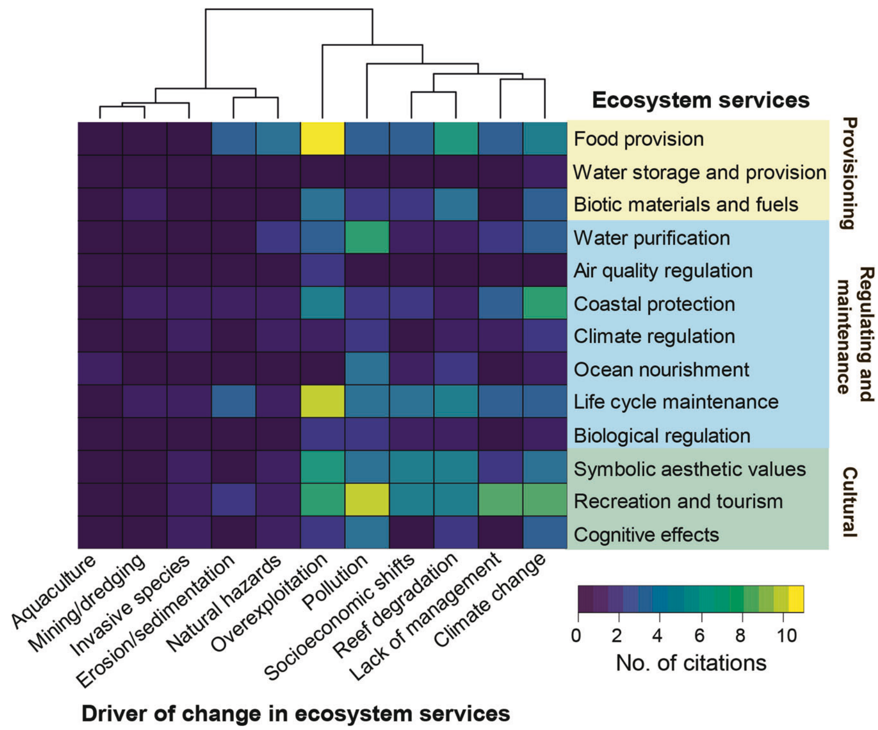

Fig. 5 Heatmap showing the frequency of drivers of change according to each category and subcategory of ecosystem service. Ecosystem services' categories and subcategories followed the classification of Liquete et al. (2013). The rank of citations per ES category is shown in Fig. S2

of the system and launching new frameworks to assess multiple and interconnected ES using reef environments as models.

The aesthetic value of a reef is driven mainly by the diversity of species and the composition of fish assemblages (Tribot et al. 2019; Pellowe et al. 2023). In this way, we verified that recreation and tourism were the most assessed subcategories of cultural ES in reef environments, usually related to reef types that display heightened aesthetic characteristics/convey elevated aesthetic appeal like coral reefs, and in high-income countries such as the United States and Australia. Among cultural ES in high-income countries, recreation and tourism have great value for their therapeutic and recreational benefits (Tielbörger et al. 2010), while in low and middle-income countries, cultural ES are more valuable for their cultural identity and dependency (Outeiro et al. 2019). The higher amount of cultural ES research observed in the Global North (Australia is considered Global North in economic terms) may be related to two main reasons. Firstly, higher-income countries have greater access to resources to conduct cultural marine ES research, like funding, technology, and technical skills (Martin et al. 2016). Secondly, a relevant fraction of ES research on marine and coastal zones/areas (Martin 2016; Checon et al. 2022), as well in terrestrial environments (Brouwer et al. 2022) of the Global South is published in other languages. The inclusion of non-English and gray literature may add more information in further reviews. Considering the amount of published research, the Global North hosted most of the research on reef ES. Research funding is limited in the Global South, contributing to the low research efforts in many fields (Trisos et al. 2021; Lebel and McLean 2018; Torres and Alburez-Gutierrez 2022).

Two gaps in the cultural marine ES research were observed in our review addressing reef environments: lack of access to more subjective and intangible cultural ES subcategories such as spiritual benefits and sense of place, and the need to investigate the role of open-ocean (high seas) and deep reefs in providing cultural ES. These gaps have been described in a previous review assessing marine and coastal cultural ES (Rodrigues et al. 2017). The extensive research on cultural ES, particularly in recreation and tourism, is likely due to their greater accessibility and quantifiable value compared to other, more subjective and intangible subcategories within cultural ES. Typically, the most frequently studied cultural ES are those that can be easily quantified (Milcu et al. 2013). Despite being the focus of extensive research in reef ecosystems, cultural ES in marine environments are still considered poorly understood, even though ~40% of the global population resides within 100 km of the coast (Martin et al. 2016; Rodrigues et al. 2017). Another gap, as previously noted by Milcu et al. (2013), is that cultural ES often encompass spiritual benefits, such as religion and myths, which are inherently subjective and intangible, making them more challenging to objectively quantify.

The gap regarding deep reefs is not only for cultural ES. Photic coral reefs (mostly <20 m deep) were the focus of most ES assessments in reef habitats, while mesophotic and deep reefs (>30 m deep) were largely left unstudied, representing less than 5% of the assessed studies. This scarcity of studies in deeper reefs is strongly related to their inaccessibility to researchers and SCUBA divers (Holstein et al. 2019), a characteristic that also constrains cultural ES such as recreation and tourism, aesthetic and cognitive effects. However, mesophotic reefs may share many ES with shallow reefs. For instance, with the overexploitation of shallow habitats, fishers can be relying on deep reefs for a continuous supply of food, and products have been discovered and used in many industries (e.g., pharmaceutics, mining). Moreover, some regulating and maintenance ES found in mesophotic reefs are complementary to those found in shallow reefs. For instance, while shallow reefs are considered important nursery habitats for the life cycle of many species, mesophotic and deep reefs are commonly used for spawning aggregations and feeding grounds (Domeier and Colin 1997).

ES research in low and middle-income countries addressed mainly provisioning as well as regulating and maintenance ES. ES related to life cycle maintenance rely on several factors that make reef biodiversity high, such as the structural complexity of macro and microhabitats and energy flux through the ecosystem to support biodiversity (Messmer et al. 2011). Oyster reefs have a lower touristic appeal and have been assessed mainly for regulating and maintenance services. Such reefs deliver important ES through water purification, life cycle maintenance, food provision, and coastal protection (Grabowski et al. 2012). Oyster reefs are the most threatened reef environment assessed in our review, since 85% of them have been lost globally (Beck et al. 2011). Research conducted in oyster reefs has addressed research priorities (Rivero and Villasante 2016), such as those linking ES and well-being and integrating different disciplines into ES assessments. By fostering collaboration and incorporating strategic assessments, we can more comprehensively evaluate the diverse array of ES oyster reefs provide.

Coral reefs are the most attractive reef environment regarding aesthetics (Haas et al. 2015; Tribot et al. 2016), which, aligned with their ecological relevance, results in attracting higher research efforts on ES and other fields. In both the US and Australia, reef environments, mainly coral reefs, provide a diversity of benefits to people for either regulating and maintenance, provisioning, and cultural ES (Hoegh-Guldberg et al. 2019). Such discrepancy in research efforts may be explained by the higher absolute budgets in reef research in these countries when compared to other parts of the world, particularly in the Global South (Trisos et al. 2021), and the relevance of coral reefs for both countries, in which they are also under a worrying scenario of reef degradation (De'Ath et al. 2012; McClenachan et al. 2017). However, other countries have a higher dependence on coral reef ES than the US and Australia. Insular countries in the Caribbean and Central Pacific are highly dependent on coastal goods and services such as tourism, food security (Waite et al. 2015), flood protection (Beck et al. 2018), and tourism (Spalding et al. 2017). Such countries need to receive more attention from managers and the global community of scientists, especially those countries that rely heavily on coastal reef goods and services. Understanding the benefits from reef ES from a spatial perspective, as well as the patterns of ES supply in a changing world is crucial to inform critical risk and environmental management decisions, and the expected benefits can be directly considered by decision-makers. Well-informed and effective management of reef environments in the Global South may contribute to ensuring reef resilience and reducing the gap to high-income economies by providing multiple ES from reef environments (Comte and Pendleton 2018).

Drivers of Change in Reef Ecosystem Services

Understanding the drivers of change in marine ES is among the priorities in the field (Rivero and Villasante 2016). There are multiple drivers of ES change, reflecting the wide range of anthropogenic pressures on natural environments. Anthropogenic factors play an important role in determining the economic value of ES (Teoh et al. 2019). As we expected, for provisioning, and regulating and maintenance ES, the main drivers of change were overexploitation, degradation, and climate change. Although our findings of the determinants of change are qualitative—thus requiring caution in the interpretation—most studies did not include in-depth analyses of the sources of change for the examined ES. Therefore, the prevalence of these drivers can indirectly result from other mentioned drivers or underlying causes, such as the lack or absence of reef management, and socioeconomic shifts. It is also important to note that both direct and indirect drivers cannot be addressed separately because they do not operate independently, but rather interact with each other to generate synergies and antagonisms (Ruiz et al. 2021). For instance, poor management and capacity shortfalls have hindered reef conservation and sustainable use strategies such as marine protected areas (Gill et al. 2017) and fisheries management (Beddington et al. 2007). One of the direct consequences is the common scenario of uncontrolled exploitation of fish stocks, which has led to a decline in fishing catches, threatening the food security of human populations in coastal regions worldwide (Eddy et al. 2021; Hicks et al. 2019).

Pollution was another relevant driver of change identified in the reef ES literature. Pollution was often connected to the supplying, controlling, and sustaining of ES and largely linked to cultural ES, particularly recreation and tourism. Ocean-based plastic pollution has recently been recognized as a ubiquitous problem worldwide (Pinheiro et al. 2023).

Another important source of pollution identified in our review is due to sewage and industrial waste discharge, which causes eutrophication and chemical contamination (e.g., Smith et al. 2017; Ingram et al. 2018). In fact, land-based pollution has been the major ongoing cause of the deterioration of reefs from tropical (Edinger et al. 1998; Kroon et al. 2016) to temperate habitats (Ling et al. 2018). The degradation of reef habitats caused by pollution, in turn, restricts the occurrence of coral-associated fish (Souter et al. 2021), a critical component of the diet of coastal and traditional human populations (Robinson et al. 2022). Also, our review identified that climate change and reef degradation can interact to produce negative consequences on ES related to tourism and recreation. Climate change has contributed to reef degradation mainly in tropical coral reefs due to coral bleaching (Morrison et al. 2020). Degraded reefs are less attractive for tourism because people commonly choose, look for, and prefer preserved locations to enjoy nature, such as colorful and healthy reef benthic species (Haas et al. 2015; Marconi et al. 2020).

Recommendations and Conclusion

This review summarizes the scientific literature regarding ecosystem and environmental services in reef environments. Despite the increasing research effort and increment of approaches to assess reef ES over the last decade, the topic remains poorly studied under the label of ES, especially in the Global South, where research funding and effort are limited. With growing threats to reef environments, there is a demand for future projections on how these ES, their values and social roles will be impacted by anthropogenic pressures and their shortcomings to conservation scenarios and objectives such as those envisioned by the United Nations' Ocean Decade and 2030 Agenda for Sustainable Development.

We verified gaps in the review that need to be addressed in reef ES research agenda: (i) knowing the more subjective and intangible cultural ES in reef environments, like contribution to mental health and symbolic services; (ii) prioritizing resources in reef ES research in low and middle-income countries where reefs are important sources of food; (iii) evaluating the role of open-ocean (high seas) and deep-reef in providing ES. An important challenge for ES assessments is to incorporate multiple and synergistic ecosystem mechanisms that provide a comprehensive assessment of reef's contributions and benefits to people. By assessing ES collectively, studies could better distinguish functions, services, and benefits and therefore avoid the double counting problem that may arise because some services (i.e., supporting and regulating services) are inputs to the production of others.

An underpinning question is whether reefs can sustain current ES in the future (Rivero and Villasante 2016). Besides causing ecological impacts such as changes in ecosystem function (Vergés et al. 2019), climate change could add novel elements to ES provision, and alter the set of ES delivered in a given area (Woodhead et al. 2019). However, most changes in ES are related to the loss of services, such as decreased food provision (Bell et al. 2013) and tourism (Arabadzhyan et al. 2021). Despite being a qualitative analysis, our study provides evidence of the main anthropogenic drivers among reef ES. Such information may guide further research, quantifying how such drivers are changing the delivery of ES.

Data Availability

The dataset is available as supplementary material.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00267-023-01912-y.

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Compliance with Ethical Standards

Conflict of Interest The authors declare no competing interests.

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