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REVIEW

How are the impacts of multiple anthropogenic drivers considered in marine ecosystem service research? A systematic literature review

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Abstract

1. In recent decades, great research efforts have been made to understand how specific anthropogenic drivers impact coastal marine ecosystems and their services. Nevertheless, we still lack a synthesis of the existing knowledge on single and multiple anthropogenic drivers impacts to coastal marine systems, which is necessary to guide future work.
2. The objective of this paper is to assess the current knowledge on the impacts of anthropogenic drivers and their interactions on coastal marine ecosystem services, with emphasis on abiotic drivers as dissolved nutrients (eutrophication or de-eutrophication), temperature (warming), pH (acidification) and oxygen (hypoxia). We performed a systematic review of the literature consisting of 164 papers using the PRISMA method (Preferred Reporting Items for Systematic Reviews and Meta-Analyses). We only include English-written papers, we exclude non-English papers to avoid potential errors in representing or interpreting scientific information due to language limitations among the authors.
3. The results show that coastal marine ecosystem service research has largely focused on single drivers, while multiple driver assessments are less common.
4. Assessments partially integrate multiple driver complexity, but they do not consider (1) relations and feedbacks between drivers; 2() social processes dynamics; and (3) temporal and spatial scales.
5. *Synthesis and applications*. We have reviewed the current scientific knowledge on how human drivers affect coastal marine ecosystem services. We found that understanding the combined effects of different drivers and considering various time and space scales is still a pending issue. Ignoring multiple drivers, their interactions and time and space scales limits our understanding of reality, and results in high levels of uncertainty. This affects policies and actions, as they rely on uncertain information. Thus, incomplete knowledge leads to poor management of coastal ecosystem services. To improve this, we propose research framework to better consider multiple drivers and time and space factors.

KEYWORDS
anthropogenic drivers, coastal marine systems, dissolved nutrients, ecosystem services, hypoxia, ocean acidification, ocean warming

1 | INTRODUCTION

Coastal marine systems encompass coastal lands and nearshore marine areas. They form the interface between land and sea, and comprise a variety of ecosystems, including coastal lagoons, tidal flats, saltmarshes, estuaries, coral reefs, rocky shores and mangroves (NOAA, 2023). The great ecological richness of these ecosystems provides highly provides a wide range of ecosystem services that support human activities, including provisioning services (e.g. food, energy, water), regulating services (e.g. climate regulation, pest regulation, water purification), cultural services (e.g. recreational, aesthetic and education) and supporting services (e.g. soil formation, nutrient cycling and primary production) (Everard, 2016; MEA, 2005). However, coastal ecosystems are facing significant threats from human activities caused by, for example rapidly increasing population growth, urbanization and economic development (Neumann et al., 2015). These anthropogenic pressures can degrade coastal marine ecosystems which could threaten the services they provide as well as the synergies and relations among services (Lagbas & DI. Habito, 2016). To mitigate threats, sustainable management practices and conservation measures must be implemented, and potential alterations of ecosystem services must be evaluated.

The provision of ecosystem services is dependent on the ecological health of an ecosystem. Human-induced changes in abiotic and biotic conditions have been shown to modulate ecosystem services (Culhane et al., 2019). In essence, human activities modify ecosystem conditions (biotic and abiotic). These changes, from here on termed 'drivers', can have impacts on coastal marine organisms. This, in turn, shapes the overall biological structure of coastal ecosystems intricately connected to the entire cascade of ecosystem services (Figure 1). Interestingly, the drivers which influence ecosystem services the most are also being altered most significantly by human activities, namely changes in dissolved nutrient concentrations (eutrophication or de-eutrophication) (e.g. Meunier et al., 2016; Peñuelas et al., 2013; Wiltshire et al., 2015), temperature (warming) (Behrenfeld et al., 2016; Wiltshire et al., 2015), pH (acidification) (Aberle et al., 2013; Flynn et al., 2015) and oxygen concentration (hypoxia) (Breitburg et al., 2009). Fully understanding the effects of multiple drivers on ecosystem services, and how these might change under predicted future climate scenarios has become a topic of urgency. Consequently, these drivers have become the focus of an increasing number of natural science and interdisciplinary studies (Bai et al., 2019; Brown, Bhat, et al., 2020; Kunze et al., 2021), but we still lack a general understanding of the relationships between drivers and how these interact and affect ecosystems and their services (Gissi et al., 2021).

Drivers are synonymously referred to as stressors (Crain et al., 2008), but in the present study we have decided to use the term driver as it includes both negative and positive impacts, in contrast to stressor which has a negative connotation. Furthermore, it is important to note that drivers do not act individually. In this context, Crain et al. (2008) described three broad categories of driver interactions for all earth ecosystems. The first category of interactions is additive, where the impact of several drivers corresponds to the sum of individual effects (Figure 1). The second category is synergistic, where the combined effect is larger than the sum of individual effects. The third category is antagonistic, with the combined effect being smaller than the sum of individual effects.

Interestingly, the studies addressing the combined effects of different drivers in coastal marine systems observed high synergy between drivers and, for example showed a strong trend towards lower biological productivity at elevated temperature and pCO_2 (Kroeker et al., 2013). Moreover, multiple driver impacts do not arise linearly, but ecosystems rather respond in a non-linear way with complex feedbacks at multiple scales (Fu et al., 2018; Gissi et al., 2021). This complexity

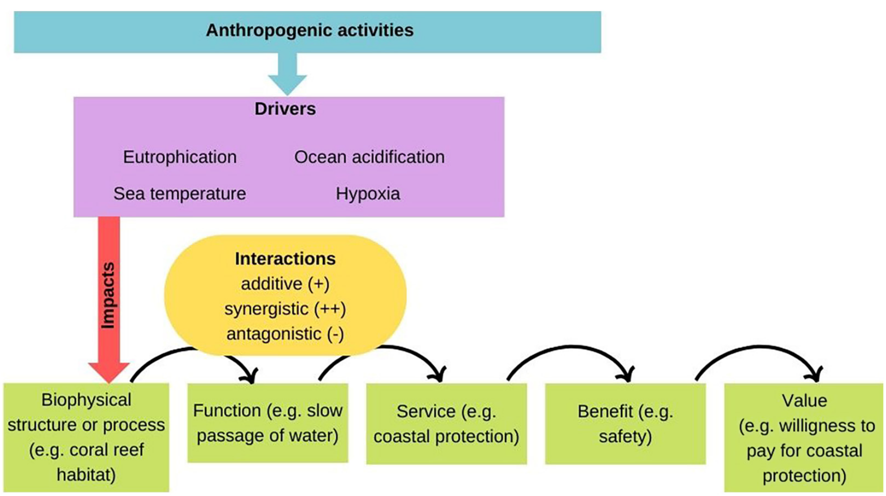

FIGURE 1 Drivers and impacts on the ecosystem service cascade. Source: Own elaboration based on ecosystem service cascade model developed by Potschin and Haines-Young (2016) and stressors classification by Crain et al. (2008).

linked to non-linearity generates vast uncertainty in coastal marine ecosystems (Hou et al., 2013). While attempts have been made to address this knowledge gap on multiple driver impacts, understanding the complex dynamics of multiple driver interactions and predicting their effects on ecosystem services is challenging. To tackle this challenge, researchers have developed several frameworks to study multiple driver impacts, such as the Driver-Pressure-State-Impact-Response (DPSIR) (Baird et al., 2016; Sanon et al., 2020). Other frameworks exist for examining the impacts of anthropogenic pressures on ecosystems, including The Millennium Ecosystem Assessment (MEA), Integrated Environmental Assessment (IEA), Cumulative Effects Assessment (CEA), Environmental Impact Assessment (EIA) and efforts to map cumulative impacts on the environment (Baird et al., 2016; Ness et al., 2010; Sanon et al., 2020). It is out of the scope of this paper to describe all these frameworks. Here, we focus on DPSIR which is used to analyse the causal relations between society and environment. It identifies the relationships between drivers (underlying causes or needs such as economic growth), pressures (anthropogenic activities derived from human needs, as use and extraction of resources, emissions, pollution or land-use change), state (effects on the biological, physical and chemical state of the environment), impacts (impacts on ecosystem functions and public health) and responses (policies addressing DPSIR). While it is a promising approach, several studies have also highlighted limitations in the DPSIR framework (Burdon et al., 2018; Patrício et al., 2016; Scharin et al., 2016; Wolanski & Elliot, 2015), such as an oversimplification resulting from the assumption of a linear and one-to-one relationship between society and environment (Patrício et al., 2016); that is, environmental problems are the result of one-to-one cause–effect link, rather than multiple complex interactions between multiple drivers and pressures. In addition, this simplification underestimates the issue of uncertainty in environmental assessments, as uncertainty is intrinsic to complex social and ecological systems (Maxim & van der Sluijs, 2011). Maxim et al. (2009) argue that DPSIR is an adequate tool to support policymakers because it allows them to better understand environmental problems but is an insufficient analytical tool because simple causal relationships cannot capture complexity. In recent years, there have been proposals to optimize the DPSIR framework to address some of its limitations (for a detailed review of these proposals see Gari et al., 2015; Patrício et al., 2016). Despite recent improvements, the DPSIR framework still fails to integrate the interactions among drivers and the effects of these interactions on ecosystem services. Thus, there is an urgent need to evaluate the direction and strength of ecosystem services alterations within the context of the multifaceted nature of anthropogenic drivers.

The failure to fully understand the complex relationships and impacts of the various anthropogenic drivers on ecosystem services can lead to ineffective management and conservation effort and in a misallocation of resources (Gunderson et al., 2016). The in-depth analysis of multiple drivers requires interdisciplinary approaches and the integration of knowledge from various fields such as ecology, economics and social sciences. The lack of understanding of these drivers and their interactions can lead to a narrow focus on certain aspects of ecosystem service management, neglecting other important factors that ultimately affect their provision. Therefore, a comprehensive understanding of the interactions and effects of multiple drivers on ecosystems is crucial for the development of effective management strategies and conservation efforts. The objective of this paper is to conduct a systematic review of the current knowledge on the impacts of anthropogenic drivers and their interactions on coastal marine ecosystem services. This review focuses on four main drivers that may strongly affect ecosystem services: dissolved nutrient concentrations (eutrophication or de-eutrophication), temperature (warming), pH (acidification) and oxygen concentration (hypoxia). Through a systematic literature review, we analyse how these drivers are taken into account in coastal marine ecosystem service research by; (1) quantifying the extent to which multiple drivers and their interactions are integrated into ecosystem services research; (2) assessing the level of integration of this research by analysing whether multi-scale and cross-scale dimensions are considered; (3) evaluating the extent to which policies and management, as well as uncertainty are studied; and (4) proposing an approach facilitating the integration of spatial and temporal multiple drivers for future coastal marine ecosystem services research.

2 | METHODS

This systematic literature review followed the PRISMA statement (Preferred Reporting Items for Systematic Reviews and Meta-Analyses; Moher et al., 2009) as means to ensure scientific robustness and reproductivity. We have used the PRISMA flow diagram (Figure 2) and a Prisma checklist to guide the review process. The

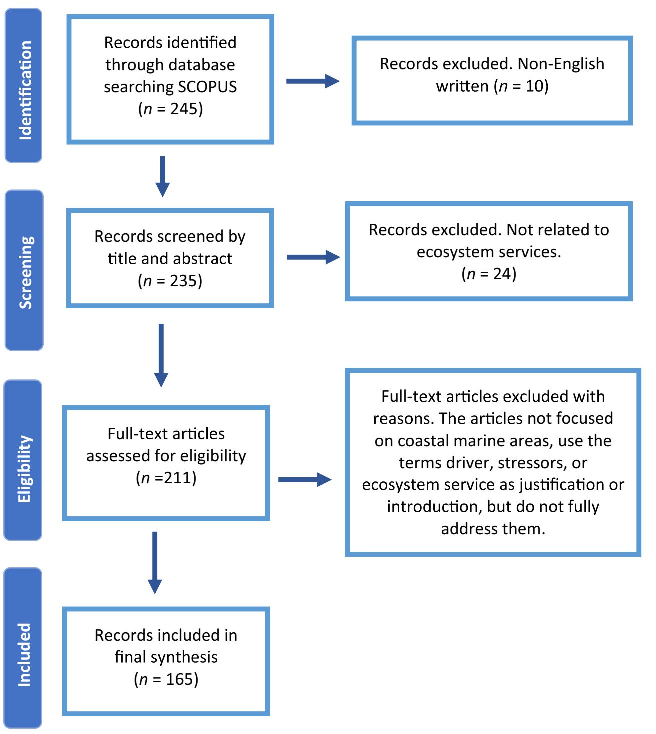

FIGURE 2 PRISMA flow diagram.

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PRISMA checklist and a systematic review protocol can be found in Appendices S1 and S2. In addition, all the data information, as the complete list of found papers and reviewed papers can be accessed through Dryad Dataset Solé et al. (2024). Ethical committee approval was not needed for this research, as this systematic review utilized secondary sources that are publicly available.

2.1 | Literature search

To identify relevant literature, we have conducted a bibliographic search in the Scopus database. Scopus is a commonly used database in systematic reviews because it provides a comprehensive coverage of academic literature across different fields and disciplines (Baas et al., 2020). It indexes a wide range of peer-reviewed journals, conference proceedings, books and other scholarly materials, and offers advanced search and filtering capabilities to help researchers identify relevant studies for inclusion in their review (Burnham, 2006). Indeed, an initial comparison of different databases at the beginning of our study revealed that Scopus provides very comprehensive literature sources. Therefore, we decided to focus on one database.

The focus of this paper is on coastal marine ecosystem services and four main drivers that may affect them: dissolved nutrient concentrations (eutrophication or de-eutrophication), temperature (warming), pH (acidification) and oxygen concentration (hypoxia). Therefore, we only considered papers explicitly dealing with this topic. We limited our bibliographical search to any peer-reviewed publication published from 2004 (year of the first paper found) to November of 2020.

The search string contained following terms in the keywords 'coastal' and 'marine', and terms related to drivers or stressors in the tittle, key words or abstract, Table 1.

2.2 | Selection criteria

For this review, we defined the following inclusion criteria: (1) analyse/evaluate/conceptualize/map/quantify/drivers of coastal marine ecosystems services; (2) publications in peer-reviewed journals; (3) publications written in English; and (4) papers focused on coastal marine areas. Through our Scopus search, we identified 10 articles written in languages other than English: 6 in Chinese, 2 in Spanish, 1 in French and 1 in Russian. Six of these papers were published by academics in Chinese institutions and linked to case studies in China, three were published by academics in Colombian and Spanish institutions and focused on the Colombian Caribbean area, and one paper published by academics in Russian institutions. Employing the same search criteria in SciELO which is an alternative open-access journal search engine, we found 99 articles in Spanish, and 28 in Portuguese. The Spanish-written papers are published by institutions from Mexico (28%, $n=28$), Colombia (24.2%, $n=18$), Chile (15%, $n=15$), Argentina (13%, $n=13$), Costa Rica (12%, $n=12$), Perú (5%, $n=5$), Ecuador (3%, $n=3$), Bolivia (2%, $n=2$), Cuba (2%, $n=2$), Paraguay (2%, $n=2$) and Uruguay (1%, $n=1$), while the Portuguese-written papers 67% ($n=19$) correspond to Brazilian publications, and 32 ($n=9$) to Portuguese publications. The inclusion of alternative open-access journal search, as SciELO and non-English languages would have improved the geographical representativity of this review. However, due to language constraints among the authors and to prevent any mistake in representation or interpretation of scientific information, we opted to omit non-English articles in our study. Automated Artificial Intelligence translations were not utilized because, at the time of the review (November 2020–April 2021), these tools were not sufficiently advanced, and potential errors in translations and misinterpretations were still prevalent.

2.3 | Data collection and analysis

We analysed 23 variables and their corresponding response categories (see Appendix S3) to assess how drivers are integrated into coastal marine ecosystem service research. We created an Excel database with 23 columns, one for each variable, and 165 lines, one for each paper. Afterwards, we reviewed all the manuscripts and filled the database. We used basic descriptive statistics to summarize the basic features of the data collected, for example count and percentages.

3 | RESULTS AND DISCUSSION

3.1 | Time and location patterns

Our review shows that the interest for drivers of change, linked to marine and coastal ecosystem services, started to increase a few years later, ca. from 2010 onwards (see Appendix S4). Liquete

TABLE 1 Search string.

Title	Key words	Title, abstract, key words	Limit to
"ecosystem service*"	"coastal" OR "marine"	"ocean acidification" OR "sea" "surface temperature" OR "deoxygenation" OR "ocean warming" OR "hypoxia" OR "acidification" OR "sea level rise" OR "temperature" OR "eutrophication" OR "human impact*" OR "impact*" OR "stressor*" OR "multiple stressors" OR "cumulative impact*" OR "multi stressors" OR "multiple impacts" OR "climate change" OR "global change" OR "global warming" OR "human impact*" OR "anthropogenic impact*"	LANGUAGE, "English"

et al. (2013) highlight that the number of papers assessing coastal marine ecosystem services has increased exponentially since 2006. Several authors consider that the publication of the Millennium Ecosystem Assessment (MEA, 2005) contributed much to the exponential growth of ecosystem service literature (Liquete et al., 2013).

In accordance with the Scientific Journal Ranking (SJR) categorization, our study explored the distribution of reviewed papers across diverse journal subjects (see Appendices S6 and S7). A significant portion of the reviewed papers (109 articles, 37%) was published in environmental science journals, followed by agricultural and biological sciences (51 articles, 17%) and earth and planetary sciences (32 articles, 11%). Social sciences covered 25 papers (9%), while multidisciplinary journals contained 22 of the papers we reviewed (7%). As the remaining papers where published in journals with a focus on economics, econometrics and finance (10 papers, 3%), as well as arts and humanities (2 papers, 1%). These results highlight the prevalence of papers in environmental science, agricultural and biological sciences, and earth and planetary sciences. Additionally, they underscore the relatively lower representation of social sciences and multidisciplinary subjects, suggesting potential gaps or less-explored research intersections.

Nearly half of the case studies we reviewed focused on marine coastal ecosystem services in Europe, North America and Asia, whereas the rest of the studies were divided between Central and South America, Australia and Africa (see Appendix S5). Global North (Australia, Canada, Western Europe, Israel, Japan, New Zealand, Singapore, South Korea, Taiwan and the United States) studies represent 48% of the papers we reviewed, while Global South (Africa, Latin America and the Caribbean, Pacific Islands and the developing countries in Asia, including the Middle East) case studies comprise 28%. The remaining articles were either global (4%) or were conceptual papers that did not study any particular location (20%).

Several studies that are not part of this review, such as Bradshaw et al. (2009), Nuñez et al. (2019), Baker et al. (2019), Melles et al. (2019), and Pettorelli et al. (2021), have analysed the publishing inequalities between the Global North and South. They have shown that the Global South is underrepresented compared with the Global North, leading to publishing disparities. One important factor responsible for the larger number of Global North studies is research funding, which is higher in wealthy countries (Pettorelli et al., 2021). Moreover, the vast majority of the research carried out in the Global South is led by authors affiliated with the Global North (Nuñez et al., 2019; Pettorelli et al., 2021), which is confirmed by our findings, except for China, where Chinese authors led the studies. Stefanoudis et al. (2021) highlighted that lower-income nations in the tropics, which are global hotspots of marine biodiversity, are highly affected by parachute science. Parachute science refers to the common practice of higher-income countries scientists who conduct fieldwork studies in lower-income countries and they do not share and communicate the results with the lower-income country scientists or institutions (Stefanoudis et al., 2021).

The literature review for this study concentrated on papers published in English, omitting those written in other languages. This decision was made to prevent any misinterpretation of results published in a language not all authors are familiar with, but it has the potential to heighten the exclusion of studies from the Global South where access to resources and opportunities to publish in English language may be restricted (Zenni et al., 2023). This bias can lead to an incomplete understanding of the provision, value and management of ecosystem services globally, especially in regions where the majority of the world's biodiversity and ecosystem services are located (Jacobs et al., 2013; Roulier et al., 2020).

3.2 | Single and multiple drivers, and ecosystem services

The majority of the papers analysed address single drivers (135 articles, 82%, $n=165$), while less than one-fifth investigated multiple driver (30 articles, 18%, $n=165$).

3.2.1 | Single drivers and ecosystem services

Eutrophication and hypoxia impacts on ecosystem services

In the papers addressing single drivers, eutrophication was the most studied (70 articles, 51%, $n=135$). Besides eutrophication, many studies focused on the effects of sea temperature rise on coastal marine ecosystem services (28 articles, 21%). Acidification and hypoxia corresponded to 13% (17 articles) and 9% (12 articles) of the papers, respectively, and a further 6% (8 articles) was not classified.

Because of its large scale and visible consequences, eutrophication has received much attention. For example, O'Higgins and Gilbert (2014), Kermagoret et al. (2019), and Luk et al. (2019) assessed the impacts of eutrophication into cultural or provision services and highlighted that the ecosystem services which are most affected by eutrophication are food provision, recreational and aesthetic services and carbon sequestration. The main reasons for the value loss of these services are the reduction in water quality and the reduction in recreational fishing landings (Armoškaitė et al., 2020; Brown, Bhat, et al., 2020). Eutrophication could also be associated with increasing occurrences of harmful algal blooms (Plutchak et al., 2010). However, disentangling natural bloom events caused by natural hydroclimatic variability, global climate change and eutrophication is difficult, and a thorough review of the relationship between eutrophication and harmful algal blooms could not reach a consensus about the role of anthropogenic nutrient enrichment in stimulating the occurrence of harmful algal blooms (Davidson et al., 2014). Thus, more research is needed to better understand the role of anthropogenic drivers on harmful algal blooms.

Hypoxia has received less attention in the articles we reviewed, although it can have severe impacts on marine ecosystems. Hypoxic conditions can lead to fish mortality, declines in commercial fish and shellfish populations, and the proliferation of harmful algal blooms that can further degrade water quality and ecosystem health (Gray et al., 2002). Hypoxia has been shown to simplify the community structure of plankton and zoobenthos and to decrease demersal fish diversity (Chen et al., 2020). In this regard, Yamamuro (2012) studied the shift from macrophytes to phytoplankton occurring in Japanese lagoons, and the resulting effects on ecosystem services and fisheries. The study found that the use of herbicides in agricultural and forestry practices was a significant driver of the shift, leading to reduced primary production, decreased water clarity, and increased hypoxia. The decline in macrophyte biomass and subsequent increase in phytoplankton biomass led to increased organic matter accumulation, which caused hypoxia in the sediments and the overlying water column.

The results of the papers we reviewed also show that eutrophication and hypoxia have important impacts on food provision, particularly fisheries and aquaculture, because insufficient oxygen concentrations result in severe habitat degradation and large-scale mortality events of commercially important fish and shellfish (Breitburg et al., 2009; Luk et al., 2019; Rogers et al., 2015). Thence, the reviewed papers highlight that deoxygenation also reduces the abundance and diversity of species that are fundamental to food security and local economies. However, more research is needed to better understand the effects of deoxygenation on fish stocks, as deoxygenation impacts can be masked by other anthropogenic effects, such as temperature rise or acidification. Some papers highlight that a certain degree of eutrophication can have positive effects on fisheries due to increased availability of organic matter; that is, additional nutrients increase food available to fished species, leading to a growth in fish stock and fisheries landings (Yamamuro, 2012). This phenomenon makes it difficult to quantify the effects of habitat degradation on fish stocks due to eutrophication (Breitburg et al., 2009).

Impacts of sea water warming on ecosystem services

The papers we reviewed addressing sea temperature rise focused on the impacts on provisioning and recreational ecosystem services, specifically on commercial and recreational fisheries. Less attention was given to the impacts on regulating services and cultural ecosystem services (six articles), other than recreational fishing, as Brown, Whiteley, et al. (2020).

Sea water temperature shapes the spatial distribution of marine species, and, as the ocean temperature increases, many species are migrating towards the poles or to deeper, cooler waters (Sunday et al., 2019). This can lead to changes in the distribution and abundance of marine species and can also disrupt established ecological interactions and food webs, which can have cascading effects on marine ecosystems. Shifts in the spatial distribution of economically relevant species are commonly addressed, as these have direct consequences for fisheries, and consequently for food provision, but also recreational fishing. For instance, studies by Sandifer and Sutton-Grier (2014), De Juan et al. (2015) and Selim et al. (2016) show that at higher latitudes, catches are increasingly composed of warmer water species, while there is a declining proportion of catches in tropical waters, where the communities are already impacted by overfishing, pollution or other anthropogenic pressures. Similarly, the shifting patterns in the pacific climate are negatively correlated to salmon survival rates. From southeast Alaska to California, there is a strong negative correlation between North Pacific Gyre Oscillation (NPGO), sea surface temperature patterns, and salmon survival (Mantua, 2015). Moreover, Sato et al. (2020) used sea surface temperature to study and model the impact of bleaching events (the expulsion of coral food-producing algae that live inside their tissues) on ecosystem services provided by coral reefs, including fisheries. The results show that coral bleaching results into a significant reduction in the potential ecosystem services provided by the reefs. Specifically, the study found that the economic value of coral reef tourism and fisheries declined by more than 90% following a severe bleaching event. Additionally, the ability of the coral reef to provide shoreline protection was also reduced, potentially increasing the risk of coastal erosion and damage from storms.

The reviewed papers also show that rising sea temperatures, especially peaks in sea surface temperature, influence the distribution of non-native species and disease-causing organisms which can lead to contact infections and seafood-associated poisonings in humans (Sandifer & Sutton-Grier, 2014). Introduced species are often the ones displaying high physiological plasticity and adaptation rates and can have a competitive advantage over native species with limited adaptation mechanisms. Rising sea temperatures may facilitate species introductions and may increase the fitness of non-native species, thus increasing the risk of establishment with negative consequences for native species (Hershner & Havens, 2008). However, it has been argued that certain non-native species might also enhance ecosystem services. For example, Neves et al. (2020) studied how certain non-native mussels enhance regulating services such as water purification.

Acidification impacts on ecosystem services

Coastal and marine research has proven that ocean acidification decreases the production of calcium carbonate by marine organisms, such as corals and molluscs (Guinotte & Fabry, 2008). This can lead to the deterioration of coral reefs and other structures that provide habitat for a wide range of marine species, including fish and other commercially important organisms. Moreover, some studies highlight that plankton, which constitute a crucial food source for many marine species, can experience reduced growth and survival due to acidification (Meyers et al., 2019; Spisla et al., 2021). This can trigger a chain reaction that affects the entire food chain, causing a decline in fish populations and reduced yields from fishing. Acidification can also impact other ecosystem services, such as the provision of coastal protection and recreation opportunities. For example, the loss of coral reefs can increase the vulnerability of coastal communities to storms and erosion, while declines in fish populations can reduce opportunities for recreational fishing and tourism (Jackson et al., 2020). The reviewed papers state that the effects of ocean acidification can be exacerbated by other stressors, such as ocean warming (Barnes et al., 2019) or nutrient pollution (Orlando & Yee, 2017), which can further impact marine ecosystems and the services they provide. Although the reviewed papers mention these other drivers, they do not address the relations between them.

3.2.2 | Multiple drivers and ecosystem services

Studies on multiple drivers, 18% (30 articles), address relations among drivers and provide a more holistic understanding of the impacts of global change on ecosystems and their services than studies on single drivers. The most frequent combination of drivers studied is between changes in ocean temperature and eutrophication (14 articles). The papers we reviewed emphasized sea temperature as a key factor influencing eutrophication processes, with larger algae bloom episodes at warmer temperatures, which negatively impact carbon sequestration, recreation and food provision services (Inácio et al., 2020; Willis et al., 2018).

The combined effect of ocean warming and acidification also received attention (11 articles) as these two drivers change synchronously in response to increasing atmospheric CO_2 concentrations. Although the combined influence of warming and acidification may affect a broad range of marine organisms and the services they provide (Harvey et al., 2013), a major share of the literature has focused on how warming and acidification may affect survival of corals (7 articles, e.g. Amaral et al., 2016). Severe heat stress causes bleaching episodes, and ocean acidification reduces the availability of calcium minerals for skeleton building and repair in corals (van Hooidonk et al., 2014). As coral reefs are associated with high biomass of commercially exploited species, the combination of these pressures threatens coral reefs' survival, and hence, aesthetic services and food provision services. In this context, most studies focus on the negative effects on externally calcifying organisms (Reef et al., 2015; Rogers et al., 2015), while the effects on internally calcifying organisms such as marine fish are less commonly studied (Gobler et al., 2018). While significant reductions in growth and survival of fish species, in particular, larval stages of Northeast Arctic cod (*Gadus morhua*) have been observed (Hänsel et al., 2020), other studies have shown no impacts for larval stages under ocean acidification (Maneja et al., 2013). Moreover, Waldbusser et al. (2011) showed that ocean acidification can lower growth rates and reduce survival of oyster larvae, which could have significant implications for the sustainability of oyster aquaculture. Barton et al. (2015) also observed that under higher acidity conditions oysters were less able to cope with changes in other drivers, such as sea temperature. Nonetheless, there is still a lack of evidence regarding the impacts of ocean warming and acidification in externally and internally calcifying organisms. More research is needed to understand how the combination of ocean warming and acidification will impact ecosystems and people who depend directly on the impacted ecosystems and their services, such as associated fisheries, aquaculture and touristic activities.

Studies on the combined effect of ocean warming and acidification also highlighted that carbon sequestration potential might be reduced. While some studies focused on the mortality and dissolution of calcifying organisms and calcareous reef remains (Rogers et al., 2015; Weijerman et al., 2018), others studied the effects of ocean warming and acidification on the carbon sequestration role of non-calcifying organisms, such as kelp forests (Smale et al., 2013, 2019). Results from Smale et al. (2013) indicated that kelp forests might benefit from changing environmental conditions because elevated pCO_2 may benefit photosynthesis and increase growth rates, and likely increase optimal thermal range (Koch et al., 2013). However, kelp forests may be outcompeted by turf-forming algae in a warmer and more acidic ocean due to their higher temperature tolerance and ability to outgrow kelp under elevated CO_2 conditions (Smale et al., 2013). Turf-forming algae can have a greater competitive advantage over kelp due to their faster growth rates and higher reproductive output, which allows them to colonize and outcompete kelp in areas where they co-occur (Provost et al., 2017). Furthermore, turf-forming algae may also benefit from increased nutrient availability in a warmer and more acidic ocean, which can further enhance their growth and competitive advantage over kelp (Filbee-Dexter & Wernberg, 2018). These factors may contribute to the shift in dominance from kelp forests to turf-forming algae in a warmer and more acidic ocean, which can have significant implications for carbon sequestration and ecosystem functioning.

Additive relations have been studied by some articles (10 articles). Singh et al. (2017) present a methodology to review the cumulative impacts of anthropogenic change on coastal ecosystem services. Their study takes into consideration the importance, magnitude and causal process of the impacts. They concluded that, despite high uncertainty in the threat posed by individual stressors and impacts, the total additive impact was consistently higher for all ecosystem services considered. Synergistic and antagonistic effects were very marginally addressed, 3 and 1 times, respectively. These include, for example, the paper by Hernández-Delgado (2015), which focuses on highly vulnerable small tropic islands, and indicates a synergistic effect of sea temperature rise combined with acidification on coral reefs. As coral reefs and other associated coastal ecosystems function as a first line of defence against storm swells, these tropical islands become even more vulnerable with reef loss. While becoming an increasingly studied topic, the additive, synergistic and antagonistic interactions between drivers and their effects on ecosystem services remain poorly understood. This is largely due to the additional complexity and uncertainty caused by each driver considered. Thus, there is a dramatic lack of information on how ecosystem services are affected by multiple driver relations.

3.3 | Spatial and temporal scale relations and ecosystem services

Ecosystem services are the result of multiple and complex relations between ecosystems and humans (Reyers et al., 2013), taking place at multiple temporal and spatial scales. However, time and space were not central elements of the reviewed papers, particularly multiscale analysis were seldom considered.

3.3.1 | Spatial scales, ecosystem services and drivers

The vast majority of single driver studies we analysed included one spatial scale, 92% (124 papers, $n=135$), while very few integrated multiple scales, 8% (11 papers, $n=135$). Generally, single driver papers focused on local scale (88%, 119 papers, $n=135$), and to a much lesser degree at regional (8%, 11 papers, $n=135$), or global scales (4%, 5 papers, $n=135$). Hence, the considered studies rather provide local knowledge on the impact of specific single drivers on ecosystem services and do not integrate the multi-scale processes and relations. In the case of multiple driver studies, single-scale approaches were also dominant (72%, 22 papers, $n=30$), while multiple-scale analyses represented less than one third of the studies we reviewed (28%, 8 papers, $n=30$). Interestingly, our review has identified more multi-scale analysis in multiple driver papers than in single driver studies. Multi-scale papers combine local and regional scales, or local and global scales, whereas very few papers integrate regional and global scales. In addition, these papers focus on a single-direction interplay between scale (e.g. from global drivers to impacts at local scale), not considering the multi-directional interplay between scales; that is, cross-scale analysis. Since the integration of multiple scales and cross-scale interactions would yield deeper knowledge of how multiple drivers acting at different scales impact ecosystem services, future studies should consider these scales and interactions for a holistic understanding of how and where different drivers transform the ecosystem service process of production and use.

The integration of multi-scale analysis in multi-driver papers can provide a comprehensive understanding of the impacts of regional and local drivers, such as acidification and seawater warming on the aquaculture production at local scale. In some cases, multi-driver papers integrated global and local scales in their analysis to study climate change-related drivers, their impacts at local scale and their interactions with local processes. For example, Huxham et al. (2017) studied how climate change drivers impact mangroves and tropical coastal forests. Mangroves provide essential ecosystem services at local scale, such as protection against coastal erosion, fisheries or ecotourism. In addition, mangroves play a crucial role in mitigating climate change by sequestering carbon. Global change drivers, such as ocean acidification, seawater warming or dissolved nutrient concentrations, are threatening these habitats. Therefore, global environmental drivers can have significant local negative impacts on mangroves and their ability to provide ecosystem services to local communities. Huxman et al. (2017) argued that the involvement of local communities is fundamental for the conservation and sustainable management of mangrove ecosystems. Local communities need to be involved in the process of developing and promoting livelihoods that do not negatively impact mangroves, but rather support their restoration and conservation, thus increasing the ecosystem services they provide at local but also global scales.

3.3.2 | Temporal scales, ecosystem services and drivers

In terms of temporal scale, our review shows that 35% (58 papers, $n=165$) of the papers integrated a dynamic temporal approach. Part of these studies assessed the historical changes and impacts of single drivers with a focus mostly set on increasing seawater temperature (e.g. Filipponi et al., 2017; Mantua, 2015). For example, papers discussed that changes in water temperature have modified the spatial distribution patterns of warm water species towards higher latitudes.

Other studies addressing multiple drivers and their cumulative impacts also integrated a dynamic temporal approach (De Valck & Rolfe, 2018; Santana-Cordero et al., 2016; Vilardy et al., 2011). These studies analysed historical environmental changes to show how drivers degrade ecosystems services and the value of these services. The temporal dimension is also addressed by exploring the consequences of different future global change scenarios and management strategies. For example, Cobacho et al. (2020) explored different future climate scenarios and adaptation measures through ecological modelling to study changes in the ecosystem services provided by shellfish reefs in the Dutch Wadden Sea. Their work indicates that non-intervention strategy will reduce ecosystem service flow, while the restocking management strategy will be beneficial under all climate change scenarios included in the study.

Some studies that integrate temporal scale suggest that successive exposure to drivers reduces the resilience of ecosystems and degrades their services (Marín et al., 2014; Troell et al., 2005). For example, Troell et al. (2005) identified a regime shift, that is, a sudden change in an ecosystem from one state into another, in shallow soft-bottom ecosystems along the Swedish west coast. This study identified that the regime shift caused fewer valuable ecosystem services, particularly aesthetic and recreational values, nutrient cycle and provisioning of habitat. Rocha et al. (2015) concluded in their review of marine regime shifts that those drivers related to food production, climate change and coastal development are the most common co-occurring causes of regime shifts and that cultural services, biodiversity and primary production are the most common cluster of ecosystem services affected.

3.4 | Policies and management of single and multiple drivers

Very few papers studied how policies and management strategies address single and multiple drivers, and how policies and management shape drivers and ecosystem services (e.g. Arkema et al., 2015; Menegon et al., 2018; van Oudenhoven et al., 2015). That is, policies and management actions aimed to reduce the impact of specific drivers (e.g. CO_2 emissions and associated warming and acidification), shape relations between drivers (e.g. between warming and eutrophication) and their impacts on ecosystems services. Management actions might result in conflicting outputs; that is, trade-offs. For example, Dade et al. (2019) suggest that reforestation policies for carbon sequestration objectives reduce crop production and, therefore, food provision services. Comparably, in coastal marine areas, the protection of mangrove areas to increase carbon sequestration and coastal protection services might reduce food provision services via aquaculture. This can be aggravated due to the existing horizontal (sectorial division) and vertical fragmentation (subnational, national, regional and local divisions) of marine and coastal governance, as it obstructs holistic management approaches.

Our review shows that, since 2010, an increasing number of studies, particularly located in the EU, developed geospatial tools and models to address multiple impacts of anthropogenic drivers. These tools aim to support decision makers on inland and coastal marine ecosystem management. The most commonly used tools include cumulative impact modelling through Artificial Intelligence for Environment & Sustainability (ARIES), Integrated Valuation of Ecosystem Services and Trade-offs (InVEST), Driver–Pressure–State–Impact–Response (DPSIR), and other tools for scenario modelling. To be a useful tool for managers, most of these studies emphasized the type and the location of anthropogenic activities which represent the highest risk for ecosystem services. For instance, Menegon et al. (2018) developed a cumulative impact assessment of the Northern Adriatic Sea. This area is highly industrialized and port activities, fisheries, coastal and maritime tourism and maritime shipping generate intense cumulative effects. However, the models developed so far still lack an integration of complex feedbacks and relations between drivers which is a key aspect for environmental policies and management. The lack of understanding of multiple drivers' relations and feedbacks provides an incomplete and deficient picture of surrounding reality and high levels of uncertainty. As a result, policies and management activities, which are based on the information yielded by such models also suffer from great uncertainty levels.

There are significant challenges to integrate complex feedbacks and relations between drivers because of (1) limited data availability of coastal and marine ecosystems (Liquete et al., 2013; Sousa et al., 2016; Veidemane et al., 2017); (2) insufficient understanding of the complex ecological functions and processes behind coastal marine ecosystem services (Chan & Ruckelshaus, 2010; Veidemane et al., 2017); (3) limited understanding on how multiple drivers in different places and at different scales combine to produce cumulative impacts on various ecosystem services (Chan & Ruckelshaus, 2010; Scholes et al., 2013). Despite this lack of information, there is an urgent need to sustainably manage coastal environments, which can be supported by the precautionary principle. This provides strategic pathways for addressing uncertainties in decision-making and asserts that the lack of full scientific certainty should not impede the implementation of cost-effective measures to prevent environmental degradation when facing serious threats (UNEP, 1992). The precautionary principle can also guide proactive decision-making even in the absence of conclusive scientific evidence (Dale et al., 2019; Rangel-Buitrago, 2023). Stakeholder engagement is also crucial for environmental initiative success, as inclusive decision-making can help to reduce and manage conflicts. It also aligns priorities, and enhances social acceptability and effectiveness of management actions (Rangel-Buitrago, 2023). Solé and Ariza (2019) pointed out that, in coastal ecosystem service research, many papers use or conceptualize participation as an approach to reduce uncertainty and better support of decision makers. Through citizen or expert participation, it is possible to obtain data on coastal and marine ecosystems (for example Fishes Project in Australia, https://www.inaturalist.org/projects/australasian-fishes or Sea Observers in Spain, https://www.observadoresdelmar.es/) (Kelly et al., 2020). Moreover, participation can also provide insights on local complex coastal ecosystem and drivers dynamics (Berkström et al., 2019; Fischer et al., 2015). Nevertheless, the literature we reviewed showed that participation is conceptualized through expert elicitation, but rarely includes other forms of knowledge, as local knowledge (LEK). Future research on multiple drivers should embrace a broader approach to participation to include local knowledge.

In summary, the precautionary principle, coupled with adaptive management and inclusive stakeholder engagement, provides a robust framework for addressing uncertainties in environmental decision making. This holistic approach not only acknowledges challenges in the Anthropocene but actively leverages them to shape resilient and sustainable environmental policies.

3.5 | Filling the gaps: Integration of multiple spatial and temporal drivers within coastal marine ecosystem services research

Our review indicates that multiple drivers and their interactions are a pending issue in coastal marine ecosystem services research. It also shows that there is a lack of integration of multiple temporal and spatial scales. However, our study reveals that papers which integrate multiple temporal or spatial scales provide a better understanding of multiple driver impacts. For instance, we have identified more multi-scale analysis in multiple driver papers than in single driver papers. Here, we suggest addressing multiple driver research through a multi-scalar approach by analysing spatial and temporal multi-scale and cross-scale processes that produce and transform ecosystem services. We propose that this approach will yield a better understanding of the constant multi-causality relations of drivers and their impacts on ecosystem services.

The understanding of the multi-causality relations among drivers needs to be integrated within existing frameworks that aim to assess the anthropogenic impacts on coastal marine ecosystems. As mentioned above, a DPSIR is widely adopted framework in coastal marine research, which was modified and developed to DAPSI(W)R(M) (Drivers-Activities-Pressures-State-Impact-Welfare-Responses-Mesures) by Wolanski and Elliot (2015) and Scharin et al. (2016). Consequently, we propose to integrate multiple spatial and temporal driver interactions and impacts on ecosystem services within DAPSI(W)R(M) (Figure 3). To this aim, we integrated, within the existing DAPSI(W)R(M) framework, multiple spatial and temporal scales and impacts on ecosystem services. We believe that this adjustment allows to understand complex and nonlinear multiple drivers interactions, in space and time, while assessing the impacts of human activities in coastal marine ecosystems. Thus, it embraces the complexity of coastal marine ecosystems and provides a system understanding, rather than studying linear

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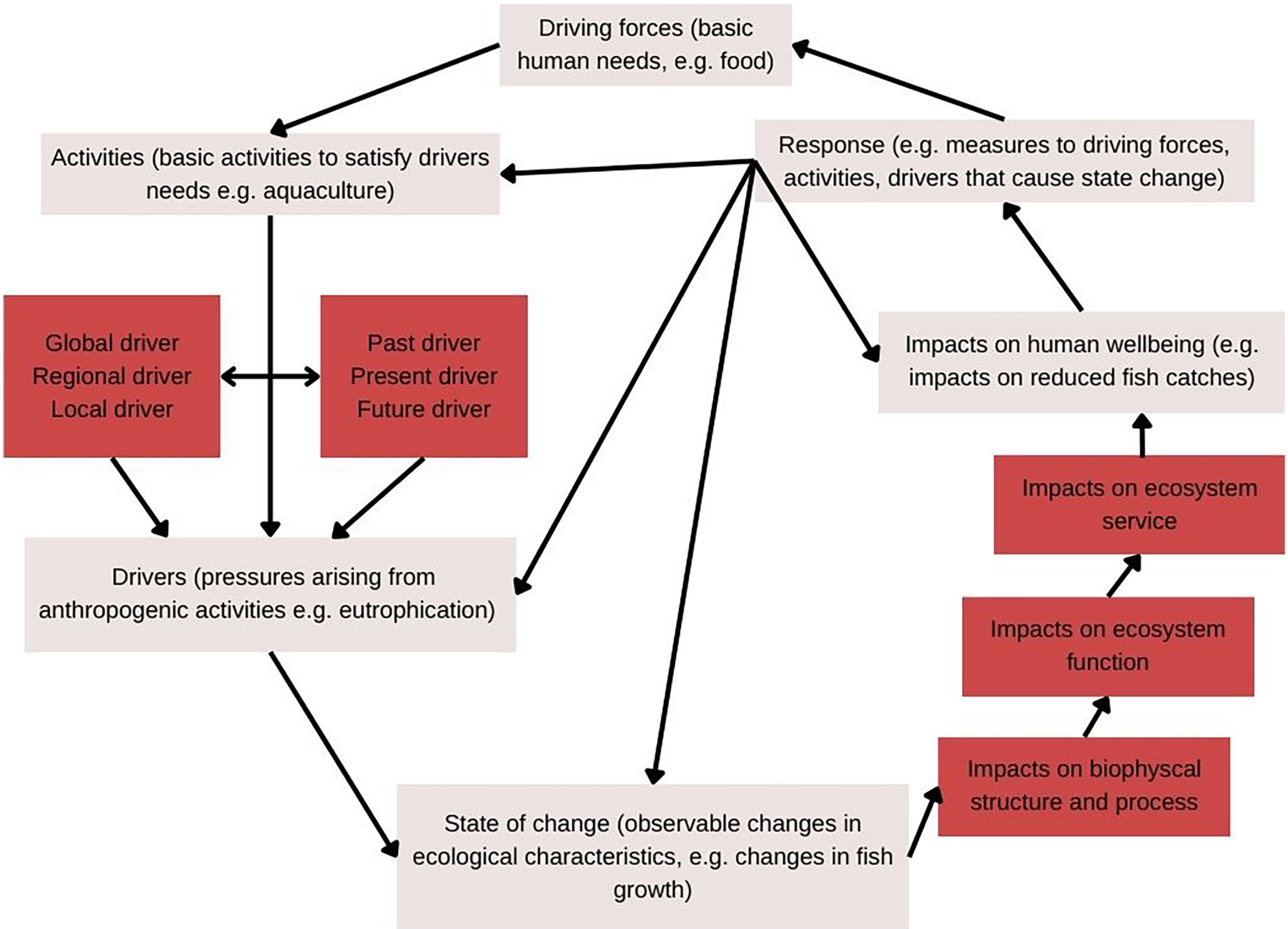

FIGURE 3 Integration of multiple driver interactions and their impacts on ecosystem services at spatial and temporal scales within DAPSI(W)R(M). In grey, DAPSI(W)R(M) steps and in red suggested steps by the authors of this paper to integrate multiple spatial and temporal scales and impacts on ecosystem services. Driving forces are basic human needs, for example access to food. Human needs are satisfied by human activities, as for example, aquaculture. Drivers (or pressures in DAPSI(W)R(M) framework) result from human activities, for example, eutrophication caused by increased nutrient runoffs. Drivers interact at different temporal and spatial scales and change the biophysical structure and processes of coastal marine ecosystems, which in turn changes their function and the services they provide. Consequently, the benefits that humans obtain from ecosystems are not the same. In response, societies develop measures and strategies to tackle these changes and limit ecosystems deteriorations. The measures transform driving forces, activities, drivers, state of ecosystems (biophysical structure, ecosystem function and services) and the impacts of these changes on human well-being.

relations and individual components. As a result, this framework goes beyond analytical tools like DPSIR (Maxim et al., 2009) and represents a comprehensive approach that also serves policymakers to better understand and tackle environmental problems.

4 | CONCLUSIONS

This literature review has identified important knowledge gaps regarding the impact of multiple environmental drivers in coastal marine ecosystem service research. We show that coastal marine ecosystem service research has largely focused on single drivers, while multiple driver assessments are less common. Moreover, assessments, which partially integrate multiple driver complexity, do not consider (1) relations and feedbacks between drivers; (2) social processes dynamics; and (3) temporal and spatial scales. The failure to integrate multiple driver complexity limits our understanding of reality and results in deficient coastal ecosystem service management. To fill this gap, we propose a conceptual framework that integrates multiple driver dynamics, socio-ecological interactions as well as temporal and spatial scales. We highlight that future studies should focus on multiple driver impact, and take into account the role of social processes, such as policies and management, in transforming drivers and ecosystem services.

AUTHOR CONTRIBUTIONS

Liliana Solé Figueras conceived the ideas and designed methodology. Liliana Solé Figueras collected the data. Liliana Solé Figueras, Emma I. Zandt, Christian Buschbaum and Cédric Léo Meunier analysed the data. Liliana Solé Figueras and Cédric Léo Meunier led the

writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

The authors have no conflicts of interest to declare. All co-authors have seen and agree with the contents of the manuscript, and there is no financial interest to report.

DATA AVAILABILITY STATEMENT

Data are available on Dryad Digital Repository via https://doi.org/10.5061/dryad.nvx0k6f01 (Solé et al., 2024).

STATEMENT OF INCLUSION

Our study was a global review and was based on a meta-analysis of secondary data rather than primary data. As such, there was no local data collection. Nevertheless, the authors have aimed to include peer-reviewed studies published around the globe. Due to language limitations only English-written papers were included. It is essential to clarify that this article primarily constitutes a literature review, as the study itself did not take place in any particular location.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Data S1: Results database search string and selected publications for review.

Appendix S1: Analyzed variables and categories.

Appendix S2: PRISMA check list.

Appendix S3: Review Protocol: Multiple global-change-driver impacts in marine ecosystem services.
Appendix S4: Number of papers reviewed in this paper published per year.
Appendix S5: Location map of the case studies.
Appendix S6: Location map of the case studies.
Appendix S7: Location map of the case studies.

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