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Key Points:

- Scientific contribution to the adaptation policy cycle needs an implementation perspective
- Adaptation research must advance knowledge in highly climate-sensitive ecoregions, across borders and sectors
- Economic barriers to coastal adaptation have been overlooked globally

Supporting Information:

Supporting Information may be found in the online version of this article.

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Enabling Climate Change Adaptation in Coastal Systems: A Systematic Literature Review

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Abstract Climate change poses increasingly severe risks for coastal ecosystems and coastal communities all around the globe. This condition requires implementing climate adaptation policy and advancing scientific knowledge to adapt to the current and future climate risks. However, implementing climate adaptation policy in coastal areas is still in its infancy. This paper provides insight into 650 peer-reviewed empirical research studies on coastal climate adaptation from the past two decades, providing global evidence on the status quo and distilling six relevant research gaps: (a) minimal contribution to the implementation phase of the adaptation policy cycle; (b) geographical imbalance toward specific ecoregions and coastal sub-systems; (c) less attention to regional scale; (d) lack of sectoral integration; (e) poor contextualization within policy and coastal governance instruments and management arrangements; (f) limited economic and financial focus. Therefore, this paper identifies areas where future empirical research can help fill current knowledge gaps and improve coastal communities' ability to adapt to climate change. This increased knowledge will enhance the resilience of coastal social-ecological systems in the face of environmental challenges.

Plain Language Summary Coastal regions are complex environments and are severely threatened by climate change. These regions are particularly vulnerable to rising sea levels, more frequent and intense storms, altered precipitation patterns, and higher ocean temperatures. These changes can pose pervasive threats to coastal communities, ecosystems, infrastructure, and economic activities. This manuscript reviews the last 20 years of coastal adaptation science and provides evidence of six areas where further research is needed. In our analysis, we adopt a worldwide scale and multidisciplinary perspective to review 650 publications and draw some conclusions and recommendations around which science could benefit coastal adaptation to climate change. Overall, we find a geographical imbalance of knowledge production which mostly neglects the global south, and that science needs to boost cooperation across borders and economic sectors and services.

1. Introduction

Coasts are complex social-ecological systems (SES) that provide essential services that contribute to individuals' well-being, support coastal communities' economic activities, and the development of the Blue Economy (Costanza et al., 2021; Jouffray et al., 2020). However, these regions are especially susceptible to the impacts of climate change, including sea level rise (SLR), more frequent and intense storms, altered precipitation patterns, and higher ocean temperatures (Cooley et al., 2022). In response to these challenges, coastal adaptation to climate change involves adjusting and preparing coastal SES to effectively respond to these impacts. The objective is to reduce risks, enhance resilience, and ensure the long-term sustainability and well-being of coastal communities. Coastal adaptation strategies typically encompass a combination of measures that address multiple aspects (e.g., physical, ecological, social, economic, educational, and governance) (Bindoff et al., 2019).

Following the ratification of the Kyoto Protocol and the establishment of the United Nations Framework Convention on Climate Change (UNFCCC) in 2005, there has been a rise in scientific publications on adaptation to projected climate change impacts (Pörtner et al., 2019). Similarly, there has been an increase in scientific focus on coastal adaptation. Despite these efforts, progress on successful adaptation remains limited, particularly in specific regions such as North Africa, Eastern Europe, Central Asia, the Middle East, and parts of South America (United Nations Environmental Programme, Adaptation Gap Report, 2021).

The complexity of coastal SES and the range of climate-related impacts create a magnitude of compounded and "wicked" adaptation challenges and the concomitant need for a range of context-specific solutions (Hinkel et al., 2018). The Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5) concluded that there is a high agreement but limited demonstrable evidence that climate change impacts on coastal human settlements and communities are reduced through coastal adaptation strategies (Wong et al., 2014). Similarly, the need for examples in the literature that assess implemented adaptation strategies was highlited in the IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) (Bindoff et al., 2019).

Recent scientific reviews on adaptation to climate change and coastal SES focus on specific policy and management topics. For example, Mallette et al. (2021) reviewed 90 scientific articles on the range of adaptation options appropriate for climate change on the coast. Toimil et al. (2020) analyzed the challenges of climate change risks and adaptation from a coastal engineering perspective. Frazão Santos et al. (2020) reviewed 153 studies and reported on marine spatial planning management challenges under climate change conditions. Olazabal et al. (2019) reviewed 226 national, regional, and local adaptation policies from around the world to establish their level of adoption and implementation. Beyond the coast, Sietsma et al. (2021) evaluated the global advancement of climate adaptation science. However substantive, these contributions are either topic-specific, rely on a relatively small sample of articles, or do not focus sufficiently on coastal systems.

At a global scale, the response from policymakers and managers from government, local communities, and the private sector to the multiple risks from climate change are varied and often inconsistent. The process for adaptation (adaptation policy cycle) is broadly agreed to consist of several linked phases (Mimura et al., 2014; Klein et al., 1999). These phases are (a) assessment, that is, analyzing the potential climate change risks and vulnerabilities; (b) planning: developing an action plan to outline goals, strategies, and actions to address the identified risks and vulnerabilities; (c) implementation: enacting policies, developing infrastructure, and implementing measures to mitigate risks; and (d) monitoring and evaluation: of planning and implementation effectiveness, including tracking progress toward achieving goals and making adjustments for the subsequent cycle adaptation. Assessing the contribution of scientific literature to the phases of the adaptation policy cycle can contribute to identifying gaps in and the need for scientific outputs to support coastal adaptation. Understanding how and where adaptation science has evolved can inform the geographical needs and nature of scientific outputs to support coastal adaptation. Furthermore, the diversity of economic sectors and services on the coast demands the supply of scientific evidence to overcome adaptation barriers and adapt policy across sectors (Arent et al., 2014).

This paper reports on the extent and nature of scientific evidence supporting the coastal adaptation policy cycle from around the globe. This work encompasses an examination of scientific literature (peer-reviewed articles), in which the findings are positioned and contrasted with related scientific research and the most up-to-date IPCC reports (i.e., SROCC, IPCC AR6 Impacts Adaptation and Vulnerability) (Pörtner et al., 2019, 2022). To effectively contribute practical knowledge to the adaptation policy cycle, it is crucial to understand where scientific efforts are currently being focused. We assess and analyze article contributions to the pool of knowledge on coastal adaptation and how it has developed since 2000. We also assess the geographical distribution of articles related to coastal adaptation and how scientific research contributes to phases of the adaptation policy cycle (Moser & Ekstrom, 2010; Wise et al., 2014). Finally, we identify different adaptation strategies and inclusion of economic sectors and services, how scientific research has been set up within coastal policy, governance, and legal instruments (e.g., UNCLOS, UNFCCC, Paris Agreement), and management arrangements.

Section 2 of this paper introduces the methodology used to compile the review. Section 3 presents the results under the sub-headings (a) geographic distribution, ecoregions and spatial scale; (b) contributions to the adaptation policy cycle; (c) trends in adaptation strategies; (d) economic sectors and services, and (e) policy, governance, and management arrangements. Section 4 discusses the essential findings and the relevance of trends and gaps. Finally, Section 5 reflects on where science should act and provides recommendations for future research on coastal adaptation to climate change.

2. Methods

A detailed description of the methodology is provided as supplementary material. Recent scholarly reviews (Berrang-Ford et al., 2021; Frazão Santos et al., 2020; Owen, 2020) and critical IPCC literature (Pörtner et al., 2019) provided the basis for defining the scope of the analytical review. The authors conducted a bibliography search of articles published between 2000 and 2021 (Figure S1 in Supporting Information S1) containing the terms "coast*," "climate change," and "adaptation" in the title and/or abstract. A total of 2,344 articles were retrieved and analyzed using the systematic review and map methodology PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) (Moher et al., 2009). The initial articles were reduced

Table 1
Categories of Adaptation Strategies (Adapted From Bindoff et al. (2019))

Categories	Adaptation strategies
Governance	Management and planning processes and instruments (e.g., institutional innovations, regulatory interventions, policy, and planning or governance models and arrangements). Examples are adopting sustainability policies, improving implementation and coordination of policies, improving Integrated Coastal Zone Management (ICZM) or Marine Protected Areas (MPAs) management, developing partnerships and building capacity.
Social and knowledge	Social and community-based adaptation responses (e.g., risk awareness, networks, public and indigenous participation, livelihoods diversification). And knowledge-based responses (e.g., integrating knowledge systems, improving scientific communication, outreach and education, capacity building, institutional and individual education).
Physical and ecological	Adaptation responses which comprehend physical, environmental, or infrastructure-based responses, or combined. Comprise adaptation solutions as technical, technological, engineering, ecosystem-based or service solutions (e.g., hard engineering (armoring), soft engineering (beach nourishment), ecosystem restoration, NBS, coastal realignment, compartmentalization, assisted evolution and relocation). Also, adaptation responses such as ecosystem restoration, protection, and bioengineering.
Economic	Adaptation responses involving monetary features (e.g., pre-investment assessments, land acquisition, public funding, payment for ecosystem services, financing, insurance, and private investments).

through evaluation of specific relevance, and the PRISMA method was used to provide summary findings of 650 peer-reviewed articles (Figure S2 in Supporting Information S1). The 650 articles were included for analysis and are the data source. To identify knowledge gaps in the coastal adaptation process, we selected publications that reported on applied empirical research with an explicit focus on coastal adaptation based on observational studies from all scales and coastal ecoregions. We extracted quantitative and qualitative data using five principal categories: (a) spatial scale and distribution across marine ecoregions; (b) contribution to different stages of the adaptation policy cycle; (c) adaptation strategies; (d) sectoral context; and (e) research framing within coastal governance instruments and management arrangements. The following section presents the results obtained from this process. We classified the adaptation strategies of coastal systems within four categories (i.e., governance; social and knowledge; physical and ecological; and economic) (Abram et al., 2019; Bindoff et al., 2019, pp. 225–226), Table 1.

3. Results

3.1. Geographic Distribution, Ecoregion and Spatial Scale

The scientific literature on *climate change adaptation* and *coastal management* has increased since 2010 (Figure S1 in Supporting Information S1). The 650 articles in this analysis included case studies distributed across 119 of 232 coastal ecoregions (Spalding et al., 2007). Based on the number of case studies, the analysis demonstrated a proportionally more significant number of articles reporting on the east coast of the USA, Australia, Europe, and Bangladesh on the Asian continent. The African and South American continents as well as the highly vulnerable low-lying island states, the Arctic, sub-Arctic and Antarctic regions received comparably little attention (Figure 1a).

In terms of the unit of analysis, case studies at the local scale were most frequent (50%), followed by subnational (29.5%), national (13.8%), regional (2.3%) (e.g., Mediterranean), continental (2.7%), and the global scale (1.7%) (Figure 1b). The majority of articles (58%) reported on "the coast" as the area of interest rather than specifying ecosystems. Combined, transitional coastal ecosystems, that is, estuaries, coastal lagoons, mangroves, wetlands, and salt marshes, received relatively greater attention (17.2%). These figures may partially be explained by their economic importance, important biological productivity and provisioning of ecosystem services, and their high climate vulnerability (Hallett et al., 2017). Studies on adaptation on small islands were relatively common (10.1%), followed by studies focusing on beaches (4.7%) (Figure S3 in Supporting Information S1). Permafrost and glaciers, both highly vulnerable coastal systems, received little attention in the adaptation literature (1.9%).

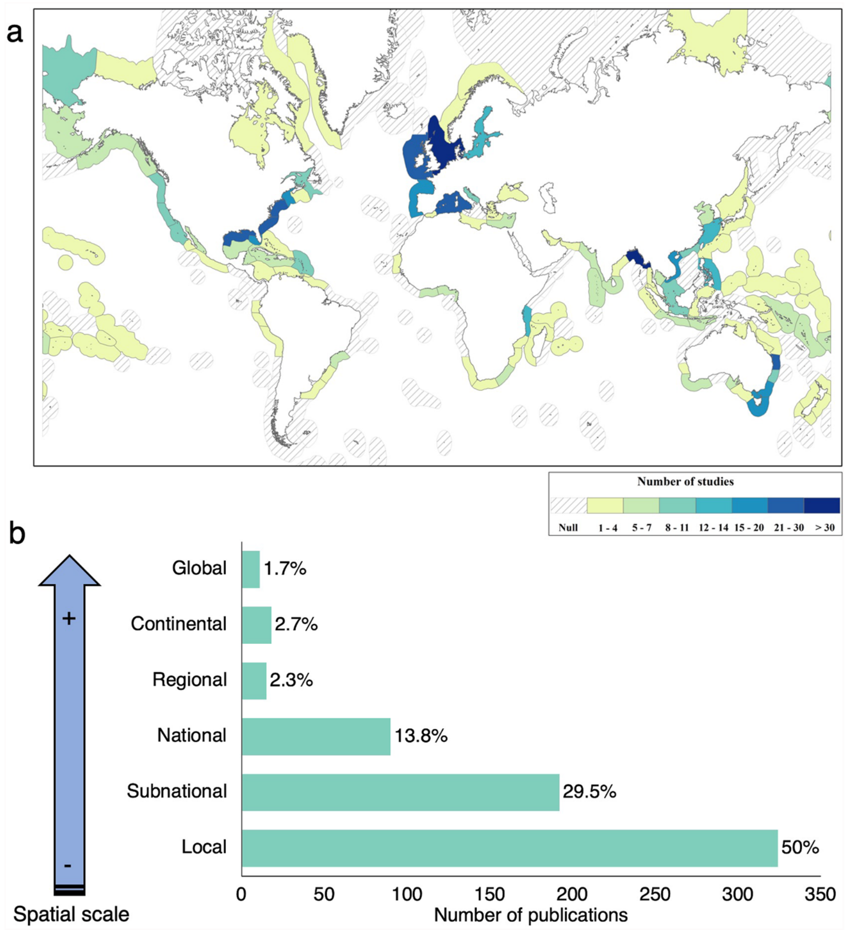

Figure 1. Geographic distribution and spatial scale. (a) Geographic distribution by ecoregion of studies reported in coastal adaptation research includes 614 publications and 826 case studies (each article can include one to several case studies at different locations). Thirty-six publications were excluded from the map, as they investigated studies on global (11), continental (12), or imprecise (13) scales. (b) Spatial scale of the case studies.

3.2. Research on the Adaptation Policy Cycle

All phases of the adaptation policy cycle are essential to achieve higher degrees of climate adaptation (Dovers & Hezri, 2010). Identifying research contributing to the different phases is insightful to understanding the priorities for scientific investment in data and information generation. Our analysis showed that none of the 650 scientific articles contributed to or informed all four phases of the adaptation policy cycle. Most articles reported on or contributed data and information to only one of the four phases (82%). Some articles reported on two phases (17%), and very few reported on three phases of the policy cycle (1%) (Table S1 in Supporting Information S1). Adaption literature most frequently (65%) reported on research that was considered to contribute to the assessment in Phase 1 of the policy cycle, 19% contributed to adaptation planning in Phase 2 and 15% to the monitoring of adaptation in Phase 4 (Figure 2a). Only 1% of articles were considered to contribute to the understanding of the implementation of adaptation in Phase 3. Across the geographic regions, the reviewed publications similarly covered the number of phases of the adaptation policy cycle (Figure S4 in Supporting Information S1).

Only focusing on the 65% of articles contributing to Phase 1, research articles covered a broad range of topics that were included under the "assessment" label: (a) stakeholders' perception toward adaptation and related aspects, including value systems (29.1%); (b) vulnerabilities (13.1%); (c) impacts (12.5%); (d) capacity for adaptation (12.2%); (e) risks (10.2%); (f) policy, governance and management (10.2%). Little attention was given to assessing adaptation-related elements such as exposure, sensitivity, costs, hazards, tools, resilience, and uncertainty (Figure 2b). Although it is true that the specific search terms used in this review may not have captured some

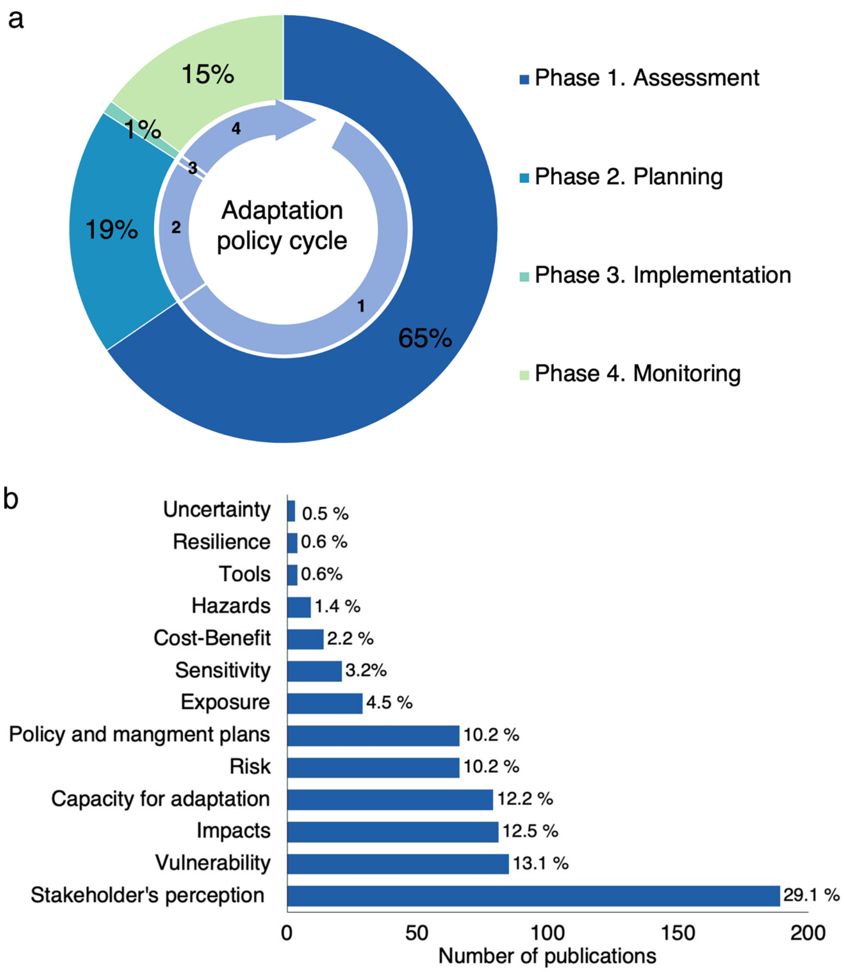

Figure 2. Contribution of research articles to the different phases of the adaptation policy cycle. (a) Percentage of coastal adaptation articles (total $n = 650$) contributing to the four different phases of the adaptation policy cycle (Moser & Ekstrom, 2010). (b) A breakdown of topics covered in the articles contributing to the policy cycle's Phase 1, Assessment.

literature focusing on risk, hazards, and related topics. In our search we have chosen to maintain a balanced representation of all disciplines by using overarching terminology associated with the adaptation policy cycle and adaptation strategies in coastal systems.

3.3. Documented Adaptation Strategies

We identified four main groups of adaptation strategies from the literature (Baills et al., 2020; Owen, 2020), and the articles were categorized according to their contribution to (a) policy and governance; (b) social practices and knowledge; (c) physical and ecological; (d) and economic. Articles also reported on different levels of engagement with these strategies, that is, making recommendations, evaluating, or implementing (Figure 3). Most of the articles reported on strategies relating to policy and governance (32.1%), followed by social practices and knowledge (26.4%), and physical and ecological strategies (26.1%). Notably, fewer articles examined and reported on strategies relating to aspects of economy and finance (15.5%). Further analysis showed that articles mainly provided insights into evaluations (53%) and recommendations (45%), while, as in Section 3.2 above, there was a disproportionate underrepresentation of articles dealing with the implementation of adaptation strategies (2%) (Figure 3).

3.4. Economic Sectors and Services

The diversity of critical economic sectors and services linked to the coast demands developing knowledge and processes to overcome adaptation barriers and adapt policy across sectors (Arent et al., 2014). We provide an analysis of the contribution of articles to coastal sectors and how the sectors have featured within research objectives.

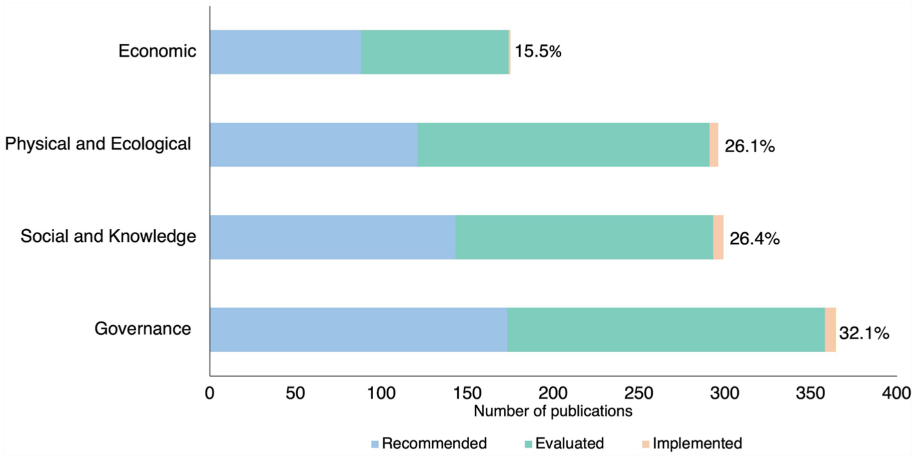

Figure 3. The proportion of articles contributing to adaptation responses are classified into four categories (i.e., governance, social and knowledge, physical and ecological, and economic). Articles were further categorized as contributing knowledge about r*ecommendations, evaluations*, and *implementation*.

Our analysis showed that most articles focused on a single economic sector or service (78.1%), while a small share covered two (18.2%), and only 3.7% of articles covered three or more (see Harrison et al., 2014) (Table S2 in Supporting Information S1). A detailed analysis shows a preference for coastal management (41.2%). Then, other relatively studied sectors and services include urban management, which also includes urban planning, engineering, and design (15.6%); fisheries (7.5%); livelihoods (7.2%); agriculture (6%); tourism (4.9%); economic and financial (3.5%); aquaculture (3.2%); water services (e.g., irrigation, water infrastructure, wastewater) (2.9%), and nature conservation (2.6%) (Figure 4). Livelihoods, even though it does not fit the canonical definition of a *sector*, was considered as a response to the relatively high number of publications, that did not take a sectoral approach but aimed to address issues such as empowering poor people, reducing poverty, and promoting economic growth through the provision of alternative livelihoods.

At a continental scale, the study of the different sectors demonstrated a similar trend, skewed toward coastal management, for the North American, Australian/Oceanian, and European continents. However, articles documenting sectors such as fisheries, agriculture, and livelihoods were proportionally more abundant for the Asian and African continents, Central and South America, and the Caribbean Islands States (Figure 5). Overall, the

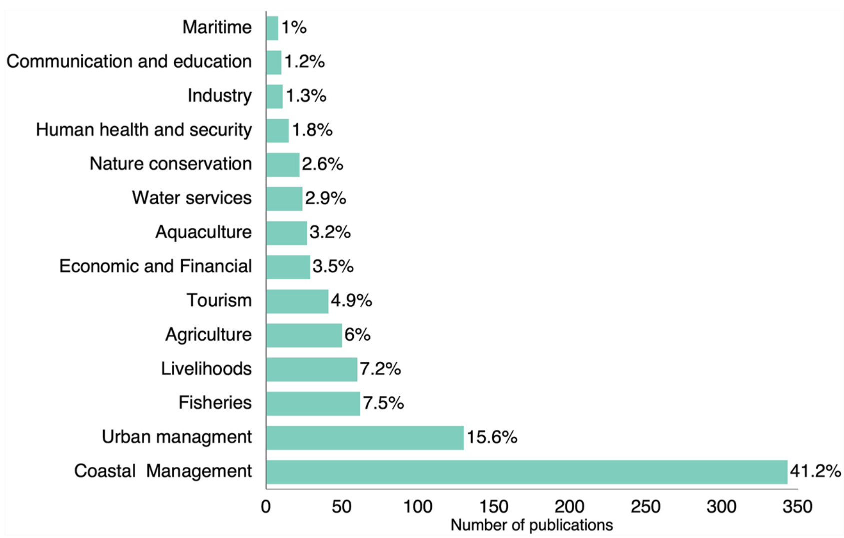

Figure 4. Percentage of articles contributing toward understanding adaptation in economic sectors and services. Articles can contribute to one or more sectors or groups of services.

10.1029/2023EF003713

Figure 5. The contribution of scientific articles to sectoral adaptation as reported in 851 case studies described in 639 scientific articles (11 publications at the global scale are not represented here).

Global South present a consistent lack of adaptation research contributing to sectors such as water services, aquaculture, financial, industry, and maritime.

3.5. Policy, Governance and Management

The results in Section 3.4 shows a large share of articles contributing to coastal management and governance issues (Figure 3). Further analysis of how the articles relate to coastal management and its policies revealed that 407 articles (58.4%) had no legal, governance, or management instrument framing. Governance and policy frameworks were most often reported as local policies or regulations (14.2%), followed by national (10.2%) and sub-national (8.3%) policies or regulations (Figure 6). This observation is consistent with spatial scales most studied in the articles (Figure 1a).

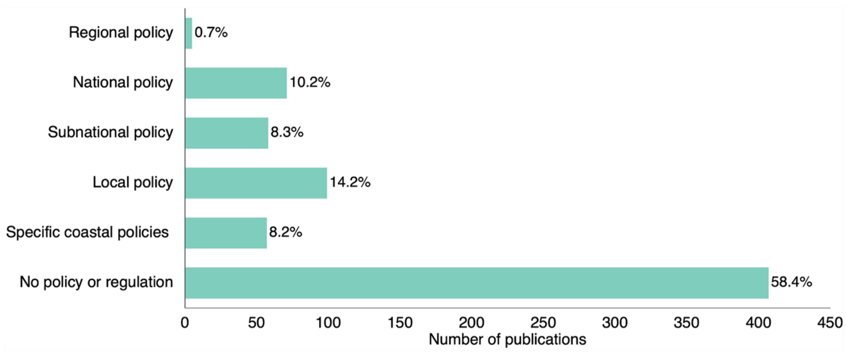

Figure 6. The framing of scientific publications by different policy contexts from local (e.g., municipal management plans) to regional (e.g., European Network Natura 2000) and specific coastal policies (e.g., MSP, ICZM, and MPA).

In general, there is a limited reported association between adaptation science and specific coastal policies (e.g., Integrated Coastal Zone Management (ICZM), Marine Spatial Planning (MSP), and Marine Protected Areas (MPAs)) (Frazão Santos et al., 2020). This is noteworthy because of the similarities between the policy implementation cycles for adaptation and ICZM, and the potential benefits of integrating coastal governance and management with climate change adaptation (Ojwang et al., 2017; Rosendo et al., 2018).

4. Discussion

From our perspective, "coastal adaptation research" contributes to assessing, developing, and testing approaches to implement actions to adapt to critical climate change risks threatening coastal SES. We analyzed how this type of research developed during the last two decades by undertaking a systematic literature review of 650 peer-reviewed articles. Results show that since 2000 there has been a gradual increase in relevant articles and, since 2005, an exponential increase in the scientific literature (Figure S1 in Supporting Information S1). Our research presents a comprehensive evaluation of coastal adaptation research instead of a narrower one of a single research element or phase of the adaptation policy cycle. This approach allowed us to report on the contribution of scientific articles to the phases of the adaptation policy cycle and the implementation of knowledge production to support climate change adaptation on the coast. This review differs from previous review efforts by the number of articles analyzed ($n = 650$), which provided robustness and confidence to the results. The results from the analysis identified six critical gaps in the research on coastal adaptation over the last two decades.

4.1. Geographic Distribution of Research

Identifying the spatial unit of analysis used in case studies indicated priorities for studying and publishing on climate change adaptation between localities and regions. Our results showed a paucity of research in some highly vulnerable territories, including the Polar Regions and the African and South American continents. The number of case studies reporting on adaptation in Bangladesh was the exception (Figure 1a). Overall, our results support the need for more research effort on coastal regions with a low gross domestic product (GDP) in the Global South, as highlighted by Arent et al. (2014).

Despite the high vulnerability, and economic and environmental importance of the Artic, adaptation measures are often reactive and need more empirical implementation across scales and sectors (Constable et al., 2022). The Polar Regions' low human population density, geographical isolation, and harsh climate pose significant economic, logistical, and technical challenges for empirical research development. Moreover, these highly climate-vulnerable areas attract increasing commercial interest and strategic positioning for various economic sectors and services, such as maritime activities, mining, oil and gas, commercial fishing, and tourism (Bender et al., 2016; Constable et al., 2022). Unique ecosystems in these areas are experiencing irreversible biophysical changes, such as glacier loss and permafrost thawing, leading to shifts in carbon flow and biodiversity distribution (Masson-Delmotte et al., 2021; Meredith et al., 2019; Schuur et al., 2015; Wassmann et al., 2011). Thus, real-time observations and research need to contribute to establishing environmental thresholds, resilience, and interactions between climate drivers and impacts to address challenges in SES, including climate-resilient infrastructure, climate-informed planning, relocation strategies, and indigenous co-management agreements (Bölter & Müller, 2016; Constable et al., 2022). Furthermore, to promote effective adaptation, diverse stakeholders should be involved, funding schemes strengthened, and indigenous and local knowledge incorporated (Dawson et al., 2020; Eerkes-Medrano & Huntington, 2021; Falardeau et al., 2022). There is high confidence that this approach can lead to more effective uptake of adaptation strategies (Constable et al., 2022).

In Africa, coastal communities are particularly vulnerable to the impacts of climate change, including financial, ecological, social, and cultural consequences (Trisos et al., 2022). Despite the existing evidence, research on coastal adaptation is scarce across the African continent (Figure 1a). This knowledge production gap hinders the development and implementation of practical solutions for addressing these communities' challenges. Our findings suggest that in the Global South, the current continental imbalance in the number of scientific publications is predominantly influenced by international cooperation and funding schemes rather than the level of vulnerability of different regions and sectors (Sietsma et al., 2021; United Nations Environmental Programme, Adaptation Gap Report, 2021). Additionally, our analysis highlights disparities at an intra-continental scale, with a more significant number of studies concentrated in countries such as Kenya, South Africa, and those around the Gulf of Guinea (Ghana, Nigeria, Cameroon, Sao Tome, and Principe and Equatorial Guinea) (Figure 1a). This lack of balance in funding for adaptation science perpetuates unequal research opportunities for African researchers, leading to inequalities in research design, participation, and dissemination (Overland et al., 2022). Our study emphasizes that funding disparities undermine climate adaptation science in Africa, potentially underestimating the impact of climate change in specific sub-regions (Sietsma et al., 2021). Therefore, adaptation science in Africa must strive toward a geographically balanced approach that considers the social, economic, and environmental vulnerabilities and knowledge necessary to support adaptation policy needs (Trisos et al., 2022).

Our findings in Central and South America (CSA) highlight a significant need for empirical research, specifically in the South American coastal areas. Moreover, this highlights the pressing need to foster adaptative capacity in these areas (Nagy et al., 2019). The lack of scientific adaptation knowledge in CSA has been reported and related to intricate social, economic, and technical constraints (Castellanos et al., 2022). Additionally, we found disparities across regions, with fewer studies conducted in Southwestern, Southeastern, and Northeastern South America. Uruguay is the only CSA country with a dedicated coastal National Adaptation Plan (NAP) and more published empirical adaptation studies (Figure 1a). One of the main reasons for this lack of adaptation research is the scarcity and difficulty in accessing data resulting from insufficient monitoring of ocean and coastal ecosystems (Castellanos et al., 2022). This knowledge fragmentation on climate adaptation is caused by project-based knowledge co-production and weak state capabilities to manage and utilize the knowledge (Ryan & Bustos, 2019). Consequently, there are significant gaps in understanding the effects of climate change, designing, implementing, and evaluating adaptation policy plans. Moreover, the impact of climate change on indigenous cultures and traditional populations and their livelihoods remains understudied. The limited research effort results in an inadequate understanding of the efficacy of adaptation, which, combined with traditional knowledge, is critical in identifying essential factors to support decision-making processes (Castellanos et al., 2022). Overall, the geographical disparities in the number and types of adaptation research and measures for the ocean and coastal ecosystems across CSA countries and regions highlight the need for more scientific research and monitoring, conservation efforts, and legislative changes incorporated into CSA countries' coastal NAPs.

In Asia, we found similar patterns to Africa and CSA. Interestingly, we found that Bangladesh reverses the trend of adaptation science in coastal regions and countries with low GDP (Figure 1a). Deeper scrutiny of the acknowledgements and funding sections of the publications in Bangladesh, we found that; (a) scientists within international networks produced publications and (b) all the publications are supported by international cooperation and funding schemes from international organizations (e.g., United Nations Environment Programme). Our review suggests that investing in international research networks and expanding funding programs (such as those offered by the World Bank and the United Nations Environment Programme) is critical for advancing scientific knowledge on climate change adaptation in the Global South and Polar Regions. Such investments can enable better access to up-to-date information on climate change, the development of technical expertise, and increased capacity, all of which are essential for supporting effective adaptation policies aimed at reducing exposure and vulnerability (Kuhl et al., 2020; Mertz et al., 2009; Pörtner et al., 2022; United Nations Environmental Programme, Adaptation Gap Report, 2021). This can also aid in reinforcing the links between research results and their application in knowledge utilisation (Arnott et al., 2020).

4.2. Regional Knowledge Integration

Drivers and impacts of climate change (e.g., sea surface temperature, sea-level rise) are not bound to jurisdiction. However, our results show that adaptation science is more frecuently reported at the local scale than any other scale (Figure 1b). It is true that adaptation goals are often expressed in terms of multiple objectives and scales of operations, which capture the complex interactions between humans and society. We acknowledge the importance of local adaptation (Aguiar et al., 2018; Schlingmann et al., 2021), but we found that there is a significant opportunity for regional coordination of adaptation knowledge to support local adaptation implementation.

The impacts of climate change on coastal systems pose governance challenges due to global and regional shifts in ecosystem services, land-based drivers, and the need for coordinated responses at different scales. Matching these challenges with existing or designing appropriate governance structures presents a different challenge in its own right (Oppenheimer et al., 2019). Thus, regional knowledge, frameworks and assessment techniques are needed to integrate cross-border impacts and fragmented information sources to overcome the isolated nature of planning models and simplify complex issues (Carter et al., 2021; Maragno et al., 2020). Nevertheless, our results show that there is a need for more publications on coastal adaptation at scales that integrate and represent climate phenomena and related impacts—both from a spatial and sectoral perspective.

A caveat to our finding dealing with spatial scales is the apparent mismatch between the scale of impacts of climate change on the coast and how scientific articles are contextualized. This trend is not, however, unique to coastal science, and a similar trend is globally observed by Berrang-Ford et al. (2021). An example of the need for regionally coordinated or integrated scientific effort are the Polar Regions (Constable et al., 2022), and low-lying island states for which the implications of climate change impacts extend across scales. In these settings, there is a need for knowledge that spans jurisdictional levels, sectors and policy domains to develop effective and efficient responses (Oppenheimer et al., 2019). Adaptation knowledge is critical in supporting adapted policy mechanisms, governance principles, and management solutions related to regional economic development, such as the Blue Economy (Adger et al., 2005; Dzebo & Stripple, 2015; Mycoo et al., 2022). For example, the maritime services sector almost always extends beyond national boundaries. As such, it needs to address infrastructure adaptation issues, managing risks, conflicts and multi-level relationships that impact the sector beyond the local or port scale (Osthorst & Mänz, 2012). Also, the coastal management sector deals with regional and trans-regional natural processes to which the integration of climate change knowledge is required. For example, the climate, directly and indirectly, affects physical-chemical conditions at multiple scales (e.g., water currents, temperature, salinity), which can drive changes in biological and ecological features, all prone to altering the environmental equilibrium of coastal ecosystem services (Calosi et al., 2017; Occhipinti-Ambrogi, 2007).

The emphasis on adaptation science framed at the local scale contrasts with the need to find regional solutions (K. Brown et al., 2017; Robert & Schleyer-Lindenmann, 2021). To effectively address technical and knowledge gaps in climate change adaptation, there is a need to develop regional and transnational research programs that focus on coupled biogeography and improved climate change predictions to understand vulnerabilities at that scale (Ali et al., 2022; Torossian et al., 2016). Moreover, there is a need to move beyond project-oriented funding schemes and establish regional climate adaptation services (e.g., Copernicus Climate Change Service) that can assist with multilateral adaptation challenges and promote consistency through effective cross-scale governance mechanisms (Den Uyl & Russel, 2017; Gattuso et al., 2018; Magnan et al., 2022).

There is an opportunity for research to support spatial integration at the regional scale, including territorial planning, policy and governance perspective, as well as the ecological scale affected by climate change. Research efforts should be designed to enhance the collaboration between intergovernmental, government and NGOs, connect people, organizations, and communities through boundary-spanning organizations, address policy inconsistencies, develop spatial coordination mechanisms, and leverage national and trans-national community and local authority networks (Cooley et al., 2022; Dzebo, 2019; Fünfgeld, 2015).

4.3. Implementation of Adaptation

Barriers to the implementation phase of adaptation include access to knowledge in suitable forms for uptake, gaps in understanding, research readiness, and institutional barriers related to multiple levels of decision-making process (Ford & King, 2015; Moser & Ekstrom, 2010). Our results showed how scientific articles on coastal adaptation presented a limited contribution to knowledge directed to apply in the implementation and monitoring phases of the policy cycle (Figure 2a). However, these findings do not necessarily imply that adaptation is not being implemented or monitored, but rather that there is little empirical evidence to support these final phases of the adaptation policy cycle. Each phase of the adaptation policy cycle is crucial to achieve successful institutional and policy change in climate adaptation (Dovers & Hezri, 2010). Thus, assessing how adaptation science contributes to the different phases of the adaptation process identifies knowledge gaps (Moser & Ekstrom, 2010; Wise et al., 2014).

Prior research has identified the limited impact of science on the planning and monitoring of adaptation as a challenge to the global capacity to mitigate climate risks (Sietsma et al., 2021). On the coast, our results show a similar pattern which also reports a remarkable paucity of scientific articles on the implementation phase (Figure 2a). Our results do not explain the imbalance in scientific reporting on different phases of the adaptation policy cycle, but there are overlapping reasons for the dearth of research on implementation and monitoring. Firstly, there is a low degree of actual implementation of adaptation plans (Glavovic et al., 2022; Olazabal et al., 2019); Secondly, there is a lack of scientific interest, and therefore reporting, on the implementation and monitoring versus the assessment phase (Serrao-Neumann, Di Giulio, Ferreira, & Low Choy, 2013); Thirdly, there are several obstacles to the participation of scientists in policy related processes (Schneidemesser et al., 2020); Fourthly, implementation and monitoring of adaptation practices are most often the responsibility of governmental agencies, which commonly publish in the form of reports rather than scientific articles. Finally, some forms of adaptation, such as private and autonomous adaptation, are more prone to be overlooked by scientific literature.

The monitoring, and final phase of the adaptation policy cycle can fill a significant knowledge gap by providing evidence of good practice and guidelines to evaluate the observed and projected benefits of each measure applied in various contexts. For example, the decision on whether or not nature-based adaptation options represent low-to no-regret solutions or even no solution at all (Magnan et al., 2022).

We suggest that more complete and balanced scientific coverage of the phases of adaptation knowledge is needed to ensure the overall success of adaptation efforts. To achieve successful adaptation, it is necessary to develop a deeper understanding of barriers to all phases of the policy cycle by reducing knowledge gaps. The scientific community can better support the policy adaptation cycle by understanding its role in function in governing coastal adaptation. This will assist them in reducing scientific compartmentalization by studying the flow of data and information throughout the process and targeting specific knowledge gaps. Moreover, a deeper understanding of how empirical adaptation science can inform and guide decision-making at each stage of the policy cycle can help ensure that resources are allocated appropriately, and strategies are developed and implemented cohesively and effectively. Furthermore, to bridge the gap between science and practice -at any level of the policy cycle- there is a need to overcome different values, interests, and perspectives and bust collaborations to combine knowledge between scientists and policymakers as between governmental and technical agencies (Liu et al., 2008; Schneidemesser et al., 2020).

4.4. Sectoral Integration

Our analysis showed that coastal adaptation science predominantly reports on single economic sectors. However, a sectoral approach (as a local approach, see Section 4.2) may result in disconnected and oversimplified solutions to cross-sectoral problems. This is especially true for the coast, where multiple users of many and diverse resources result in complex feedbacks within overlapping spatial and operational areas (Juschten et al., 2021). By resolving the primary coastal sectors, our findings suggest a disconnection between adaptation science and some important economic sectors. We identified that coastal adaptation articles focus on the coastal management sector. Nonetheless, other economic sectors classified as critically threatened and increasingly vulnerable in the last IPCC report (Pörtner et al., 2022) included human health (Costello et al., 2009); maritime (Monios & Wilmsmeier, 2020); industry (e.g., heavy industry), and communication delivery (Moser, 2014) that individually were covered in less than 2% of the reviewed articles (Figure 4).

While it is essential to have specialized knowledge in particular disciplines of adaptation science, that is, in specific sectors or disciplines, having a comprehensive understanding of adaptation across sectoral interests is essential for the overall effectiveness of the process (Preston et al., 2015; Sietsma et al., 2021). Adaptation becomes systemic with cross-sectoral and cross-scale knowledge-sharing and capacity-sharing between diverse networks. Conversely, a narrow sectoral implementation of adaptation strategies may compound risks and vulnerabilities beyond single economic sectors and services (Martinich & Crimmins, 2019).

On the coast, with a high degree of the imbrication of sectors, the potential divergence of objectives may pressure decision-makers to trade off conflicting resource uses and multiple disputes (Therville et al., 2018). In this charged governance landscape, for increasing the effectiveness of climate change adaptation strategies, sectoral policies, and programmes must explicitly incorporate adaptation to climate change (Biesbroek et al., 2010; Lebel et al., 2012). This requires the better engagement of researchers across government agencies to align the production of knowledge, needs, interests, and objectives (Tompkins et al., 2008; Ultee et al., 2018).

Mapping economic sectors reported in adaptation research shows a similar pattern across Europe, North America, and Australia. However, Africa, CSA, and Asia present a tendency for adaptation science to individually approach critical primary economic sectors such as fisheries and agriculture. In the Global South, research needs to provide multi-sector governance knowledge and approaches, which have been acknowledged to support long-term adaptation prospects (Chu et al., 2016).

For example, a comprehensive, cross-sectoral strategy that integrates multiple knowledge systems is essential for addressing the challenges of adapting to SLR (Oppenheimer et al., 2019). This issue involves multiple stakeholders with conflicting interests where adaptation science can contribute to overcoming sectors frictions by integrating climate models and scenario discovery techniques to resolve better the complex interactions between economic sectors and services and the impacts of climate change (C. Brown, et al., 2014; Morris et al., 2022). Ultimately, given the challenges to cross-sectoral adaptation on the coast, our results suggest that scientific research can contribute from purely methodological aspects to policy integration and include:

1. Developing "pragmatic science" integrating multiple disciplines and multiple knowledge systems (Glavovic et al., 2022; Kopp et al., 2019; Serrao-Neumann, Crick, et al., 2013; Serrao-Neumann et al., 2021).
2. Integrating climate models and scenario discovery techniques to portray better the complex interactions between economic sectors and climate change fields (C. Brown, et al., 2014; Morris et al., 2022).
3. Developing multi-hazard and cross-sectoral methodologies to reduce the uncertainty of the scenarios and models (Fuldauer et al., 2021; Rounsevell et al., 2021).
4. Bridge gaps between science, policy, and practice by experimenting with novel approaches for engagement for collaborative problem-solving and working across organizational, sectoral, and institutional boundaries (Cooley et al., 2022; Fuldauer et al., 2021).
5. Connect with networks for information sharing and access to specialized knowledge and climate services which is critical for cross-sectoral policy integration (Biesbroek, 2021).
6. Increase the engagement with the private sector to increase the participation of scientists in real-life adaptation planning (Rosenzweig et al., 2011).

Furthermore, effective cross-sectoral adaptation governance requires political will (Hoel & Olsen, 2012) and effective coordination and transparency in policymaking, planning, and financing amongst government agencies, civil society, and the private sector (Oppenheimer et al., 2019).

4.5. Adaptation and Coastal Governance

There is general agreement on incorporating climate change information into coastal management and governance to ensure the resilience and adaptive capacity of coastal ecosystems, communities and sectors (Carvalho et al., 2013; Frazão Santos et al., 2020; Santos et al., 2016). Our results show that most scientific articles in this review lack any policy context (Figure 6). While if there is specific recognition of a policy setting, it is mainly focused on the local scale and only rarely builds on established frameworks such as ICZM (Celliers et al., 2013; Tobey et al., 2010; Van Assche et al., 2020), MSP (Frazão Santos et al., 2020; Gissi et al., 2019), and MPA (Wilson et al., 2020) (Figure 6).

The limited number of articles framing adaptation research within definite specific coastal policies may be a product of the limited scientific interest in the implementation of coastal adaptation policies (Olazabal et al., 2019), as well as limited focus on integrated land-to-sea governance systems, for example, integrating ICZM and MSP (Den Uyl & Russel, 2017; Maragno et al., 2020). The coastal management policy cycle is virtually indistinguishable from the adaptation policy cycle (O'Mahony et al., 2020), thus merging ICZM and adaptation can contribute to (a) accommodating cross-sectoral adaptation needs (Khan et al., 2016; Maragno et al., 2020); (b) developing a systemic approach informed by climate risks (S. Brown, et al., 2014; Olazabal et al., 2019); (c) developing mechanism to give a more central role to climate change adaptation and reducing the disconnection between land

and ocean management (Palutikof, Leitch, et al., 2018; Palutikof, Rissik, et al., 2018), (d) contribute to developing and disseminate climate services and knowledge that are useful and useable for coastal governance and management across different spatial scales and stakeholders (Celliers et al., 2021; Rodríguez-García et al., 2022; Tribbia & Moser, 2008).

An increasing scientific effort is devoted to bridging the gap between climate change data and information, and decision-making, for example, in MPA management (Cooley et al., 2022; Hewitt et al., 2017; Le Cozannet et al., 2017). However, information on climate change is only gradually being incorporated into policy. For example, Directive 2014/89/EU was the first European Union legal instrument to propose a framework for MSP that articulates adaptation and mitigation measures across the member states (European-Union, 2014). Nonetheless, the uptake of these measures at the national level remains muted, and adaptation to climate change is only now beginning to emerge, for example in the Spanish MSP (MSP Royal Decree, 28 February 2023).

Framing research within the existing policy is essential because; (a) it helps ensure that the research is relevant and valuable to policymakers and stakeholders; (b) researchers can better understand the policy goals and objectives, as well as the challenges and opportunities associated with policy implementation; (c) can identify gaps and help to inform the development of new policies or the revision of existing policies. Furthermore, framing research within existing policies is essential because it helps to ensure that research is relevant, helpful, and impactful in addressing policy challenges and promoting evidence-based policymaking.

4.6. Economic Barriers to Adaptation

Our analysis showed a distinct dearth of economic research related to adaptation (Figure 3). There were several related topics covered in the scientific articles, including the definition of the cost-benefit of investment in the infrastructure (André et al., 2016; Chow, 2017), exploration of alternative adaptation practices (Creach et al., 2020; Lopez-Doriga et al., 2020), evaluating costs of climate-related impacts and damage (Hinkel et al., 2014; Lin et al., 2013), and the identification of economic tipping points as triggers of adaptation (de Ruig et al., 2019; Franck & Amen, 2009). Other topics less frequently identified included; funding instruments (Bisaro & Hinkel, 2018; Pauw, 2017), leveraging private finance (Bisaro et al., 2020), and the finance archetypes (Moser et al., 2019).

There was a general agreement on the need for knowledge relating to the economy and finance-focused solutions for coastal adaptation. This included (a) the development of strategies to overcome the adaptation funding gap (Ware & Banhalmi-Zakar, 2020), (b) the transnational financing and funding schemes (Magnan et al., 2022), and (c) the assessment of the economic impacts of extreme and abrupt/irreversible events (Collins et al., 2019). The need to understand the effects of climate change on economic development, from the household to the country level, and to quantify the relationship between adaptation costs and adverse events (Castellanos et al., 2022) is particularly relevant to the Global South and small island states.

Whilst the impacts of climate change on the coastal and blue economy sectors are a priority for the sustainability of the ocean-based economy, mainstream adaptation financing remains a wicked problem brought on by geographical, social, cultural, institutional, political, and economic complexity (Bennett et al., 2019; Mycoo et al., 2022). Thus, for adaptation research, it is also essential to consider a much greater emphasis on overcoming financial and economic barriers to adaptation capacity as those of effectively implementing the complete adaptation policy cycle, especially talking the implementation area where the paucity of climate finance constitutes itself is a barrier to accessing to climate finance.

Understanding coastal adaptation's economic and financial implications is essential in identifying and prioritizing cost-effective and sustainable adaptation strategies (Bhandary et al., 2021; Carvalho et al., 2013). This knowledge can also inform decisions on financing and investment, including using public and private funds and insurance mechanisms, to ensure equitable distribution of benefits and costs among communities and stakeholders. Moreover, new financing models like green bonds can facilitate private sector investment and mitigate financial risks associated with climate change (Bisaro & Hinkel, 2018). Overall, economic and financial knowledge is critical for developing effective and sustainable coastal adaptation solutions that promote innovation, cost-effectiveness, and equity.

5. Conclusion

This paper presents a systematic review of the advances of adaptation science in coastal systems from across the globe. Different adaptation strategies and responses help reduce climate exposure and vulnerability.

Implementation depends upon the availability of adapted scientific knowledge and the capacity of the governance and decision-making processes (Pörtner et al., 2022). The role of science in support of climate change adaptation is unequivocal, and the scientific literature supports many advances across the climate adaptation policy cycle.

This systematic literature review used a large sample of published scientific articles and has uncovered a near-exponential growth in publications on climate change adaptation in coastal areas. It has also reported and distilled six critical knowledge gaps, which may be taken up by future research to support climate adaptation in coastal areas: (a) uneven distribution of research among vulnerable regions (e.g., polar), (b) particular focus on knowledge development around the assessment phase of the adaptation policy cycle with limited contribution to the implementation phase, (c) adaptation science primarily works at local scale resulting in the overlooking of adaptation challenges at regional and broader scales, (d) lack of cross-sectoral view and integration, (e) limited framing of adaptation research within coastal governance and management arrangements (e.g., MSP, ICZM, MPAs), and (f) limited focus on economic and financial conditions. The paper has also identified critical fields of interest that are enablers of the coastal adaptation policy cycle. It proposes actions to understand climate change adaptation on the coast through the lens of transformative, multi-sectoral and cross-scale governance, emphasising regional environmental governance and managing adaptation initiatives. Overcoming these knowledge gaps can potentially revert to increasing the effectiveness of coastal adaptation strategies and responses around the globe.

Data Availability Statement

The maps were generated using ArcGIS version 10.8.1 mapping and analytics software. The software is licensed to and resident at Helmholtz-Zentrum Hereon, Germany. The data used for this study is available through the Zenodo repository at Cabana et al. (2023).

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