Ecosystem services from shellfish reefs as a nature-based solution: a global evidence synthesis to guide restoration and policy

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Abstract

1. *Context.* Shellfish reefs, comprising oysters, mussels, clams, and mixed bivalves, act as ecosystem engineers and nature-based solutions (NbS), providing supporting, regulating, provisioning, and cultural ecosystem services (ES). Yet, despite rapid growth in restoration practice, the translation of ES evidence into policy and management remains uneven across regions and taxa.

2. *Objectives.* We systematically synthesized global evidence to (i) classify ES delivered by shellfish, (ii) link restoration approaches and techniques to reported ES, (iii) quantify policy mentions and governance frameworks, and (iv) identify regional and taxonomic gaps constraining applied uptake.

3. *Methods.* We quantitatively assessed how research on shellfish ES and restoration has evolved over the past two decades, identifying biases and missing linkages between ecological evidence, ecosystem service assessment, and policy uptake. This approach enables a systematic evaluation of progress toward integrating restoration outcomes into governance frameworks.

4. *Results*. Evidence is dominated by regulating and supporting services, particularly water filtration, nutrient removal, habitat provision, and coastal protection, while provisioning and cultural services remain limited. About 75% of studies address restoration, mainly active or hybrid approaches (substrate addition, seeding, engineering, community engagement), with monitoring reported in only one-sixth. Roughly three-quarters cite a policy framework, dominated by regulatory and governmental instruments, with market-based tools emerging. Stakeholder engagement appears in about one fifth of studies, often

tied to cultural services. Research and policy linkages remain weak for mussel and clam systems and across the Global South.

5. *Synthesis and applications.* To enhance the policy relevance of shellfish-based NbS, restoration should integrate socio-ecological goals through hybrid approaches, standardized monitoring, and participatory design. Linking restoration outcomes with market-based and regulatory instruments, such as nutrient credits and green-infrastructure standards, can strengthen implementation. Expanding research and investment in under-represented regions of the Global South would enable shellfish reefs to deliver equitable, multi-benefit outcomes for biodiversity, coastal protection, and human well-being.

Keywords: oyster reef; mussel bed; bivalve restoration; nature-based solutions; coastal policy; marine restoration.

Introduction

Coastal ecosystems support human well-being by buffering storms, improving water quality, supporting fisheries, and sustaining cultural identities (Barbier et al., 2011; Cooley et al., 2022). Yet, they are among the most degraded ecosystems globally, with over 85% of historical oyster and mussel reefs lost through overharvesting, pollution, eutrophication, and coastal development (Beck et al., 2011; Zu Ermgassen et al., 2012). This degradation has diminished the ecosystem functions and services that once regulated nutrient cycling, stabilized shorelines, and maintained biodiversity (Coen et al., 2007; Fodrie et al., 2017; Piehler & Smyth, 2011). Rebuilding these functions has become a central challenge for both biodiversity conservation and climate adaptation agendas (Spalding et al., 2014; Morris et al., 2018).

Among coastal restoration options, shellfish reefs, formed by oysters, mussels, clams, cockles, and mixed bivalve assemblages, are increasingly recognized as Nature-based Solutions (NbS) that integrate ecological recovery with societal benefits through ecosystem services (Baggett et al., 2015; Gentry et al., 2019). Throughout this paper, we use the term "shellfish reefs" to refer broadly to biogenic habitats formed by bivalves, encompassing what different regions describe as beds, banks, or reefs. We adopt this terminology due to its widespread use in restoration literature. As ecosystem engineers, shellfish filter and retain nutrients (Piehler & Smyth, 2011), trap sediments (Scyphers et al., 2011), provide habitat for other organisms (Coen et al., 2007; Smith et al., 2023; Benjamin et al., 2022), and protect coasts from erosion (Scyphers et al., 2011; Spalding et al., 2014). Consequently, they contribute to supporting and regulating services (e.g. habitat provision, water filtration, coastal protection) and, when locally valued or co-managed, to provisioning and cultural services (e.g. food, heritage, identity) (Brumbaugh & Coen, 2009; Coen et al., 2007). Restoring mussel reefs not only rebuilds habitat structure and function but also may reactivate carbonate buffering and dissolution processes, enhancing local chemical resilience and long-term ecosystem stability (Powell & Klinck, 2007). Through shell dissolution, CO_3^{2-} ions are released, increasing alkalinity and mitigating acidification in coastal waters (Waldbusser et al., 2013). This process underlies the taphonomic feedback hypothesis, whereby shell accumulation promotes further calcifier settlement and carbonate cycling, sustaining shellfish reefs over time (Kidwell & Jablonski, 1983).

Despite the well-recognized ecosystem functions of shellfish reefs, the integration of ecosystem-service evidence into restoration planning and policy remains limited (Coen & Luckenbach, 2000; Mach et al., 2015). While numerous projects demonstrate ecological success, few explicitly evaluate social outcomes or translate findings into operational policy instruments such as nutrient credits, living-shoreline standards, or green-infrastructure incentives (Baggett et al., 2015; Barrett et al., 2022). Monitoring and evaluation are rarely reported, and most studies lack comparable outcome measures, limiting the ability of agencies to justify investments or track progress toward global biodiversity targets (Coen et al., 2007; Luckenbach et al., 2005).

Although there is growing global interest in shellfish restoration, the distribution of research effort and implementation remains globally uneven (Fitzsimons et al., 2020; Gillies et al., 2020; Toone et al., 2021). Most initiatives have emerged in temperate regions with established restoration programs and stronger institutional capacity (Beck et al., 2011; Morris et al., 2018), while many biodiversity-rich coastlines in developing regions remain poorly represented in the scientific and policy record (La Peyre et al., 2015; Spalding et al., 2014). This imbalance raises concerns about the scalability of ecosystem-service knowledge and limits the integration of shellfish-based NbS into diverse socio-ecological contexts (Gentry et al., 2019; Fitzsimons et al., 2020).

Recent international frameworks, such as the Convention on Biological Diversity's Kunming-Montreal Global Biodiversity Framework (Convention on Biological Diversity, 2022a), the EU Marine Strategy Framework Directive (European Parliament & Council of the European Union, 2008), and the UN Decade on Ecosystem Restoration (United Nations, 2019), reinforce the urgency of restoring degraded coastal ecosystems and aligning restoration with ecosystem-service delivery (Convention on Biological Diversity, 2022b; European Commission, 2025; Waltham et al., 2020). However, a comprehensive synthesis explicitly linking restoration approaches, ecosystem-service outcomes, and policy dimensions for shellfish systems is still lacking. Addressing this gap will help identify and promote processes that better integrate ecological and governance dimensions of restoration.

Here, we conduct a systematic evidence synthesis to evaluate how shellfish restoration contributes to ecosystem-service delivery and how it intersects with policy and governance worldwide. By synthesizing ecological, policy, and governance dimensions—and incorporating social information where reported—this study provides a global overview of how restoration practices translate into decision-relevant outcomes. Specifically, we address the following research questions: (RQ1) Which ecosystem services are most consistently evidenced across shellfish ecosystem types? (RQ2) Which restoration approaches and techniques co-occur with particular ES outcomes? (RQ3) How and where are policy frameworks, instruments, and stakeholder groups mentioned in relation to shellfish restoration?, and (RQ4) Which geographic and taxonomic gaps persist in the evidence base, and what do they imply for scaling shellfish-based NbS across wider geographies and diverse socio-ecological contexts?

We expected that active and hybrid restoration approaches—such as substrate addition, seeding, and habitat engineering—especially when combined with community engagement, would yield more diversified portfolios of ecosystem services and stronger policy visibility. In contrast, we anticipated that passive approaches and regions in the Global South would exhibit limited monitoring, weaker governance linkages, and lower integration of ecosystem-service metrics into policy frameworks. By addressing these questions, our study provides, to our knowledge, the first global synthesis linking restoration techniques, ecosystem-service outcomes, and policy instruments for shellfish ecosystems, offering a practical foundation for scaling nature-based solutions that integrate ecological restoration with more inclusive and effective governance.

Methods

This systematic review aimed to synthesize global empirical evidence on the ecosystem services provided by natural and restored shellfish ecosystems, the restoration practices supporting them, and the extent to which these services are integrated into policy and governance frameworks. We conducted a systematic evidence synthesis following the ROSES (Reporting Standards for Systematic Evidence Syntheses) guidelines (Haddaway et al., 2018). The search was carried out in the Web of Science Core Collection, covering all years indexed up to December 2024. We used the Boolean query:

("ecosystem service*" OR "ecological function*") AND

("mollusk bank*" OR "shellfish reef*" OR "bivalve bed*" OR "shellfish*")

This search returned 352 records. Records were screened in two stages: (i) title and abstract, and (ii) full text. We applied predefined inclusion and exclusion criteria (Table S1), ensuring studies (i) explicitly evaluated ecosystem services (ES) from natural or restored shellfish reefs/banks, (ii) employed recognized ES classification frameworks (MEA, 2005; TEEB, 2010) or reported ES metrics, (iii) provided empirical evidence (quantitative or qualitative), and (iv) discusses implications for, or mentions policy, or restoration. We excluded papers focused exclusively on aquaculture, non-bivalve ecosystems (e.g., coral reefs, mangroves, seagrasses), or non-empirical contributions such as opinion pieces and conceptual essays. Screening and data extraction were independently verified by two reviewers to ensure consistency. A random 10% of records were double-checked for coding accuracy, and any discrepancies were resolved through discussion. After screening, 151 studies were retained for analysis (Fig. S1; see Table S2 for a summary of ROSES reporting items).

From each included study, we extracted four sets of descriptors:

1. **Study context**: year of publication, country, spatial scale (Table S3), and ecosystem type (oyster reefs, mussel beds, clam beds, scallop habitats, cockle beds, mixed bivalve reefs or shellfish general; Table S4).

2. **Ecosystem services**: coded according to MEA (2005) and TEEB (2010) into supporting, regulating, provisioning, and cultural categories, with sub-keywords such as water filtration, nutrient removal, habitat provision, food production, and education. Both quantitative (e.g., nitrogen removal rates, species richness) and qualitative evidence (e.g., community well-being, heritage values) were recorded (Table S5).

3. **Restoration practices**: approach (passive, active, hybrid), techniques (e.g., substrate addition, reef seeding, habitat engineering, community engagement, stressor removal, habitat protection), restoration objectives (habitat restoration, biodiversity enhancement, ecosystem function recovery, coastal protection). We also noted monitoring and evaluation approaches, understood here as the long-term and systematic observation of restoration outcomes rather than short-term measurements of ecological variables commonly reported in experimental studies,

including citizen science participation and adaptive management (Table S6). Where applicable, we also coded nature-based solution attributes for building resilience (climate mitigation, coastal protection, water quality, and removing nutrients; Table S7).

4. **Policy variables**: binary coding for policy mention (yes/no); name and type of instrument (regulatory, market-based, certification, program/initiative, framework policy, or management approach such as ecosystem-based management); scale (local, regional, international); policy thematic area (fisheries and aquaculture, habitat and biodiversity, environmental quality, management and governance); policy function (conservation, restoration, regulation, incentives, planning, participation); stakeholder involvement (public sector, private sector, indigenous peoples); and engagement methods (public consultation, participatory interaction, co-management) (Table S8).

All extracted information was compiled in a standardized spreadsheet with controlled vocabularies for ES categories, restoration attributes, and policy variables to ensure traceability and reproducibility. Metadata and coding definitions are provided in Tables S3–S8.

We used descriptive and comparative analyses to identify temporal, geographical, and thematic patterns across the evidence base. Temporal trends were summarized by year of publication. Geographic distribution was mapped as country-level counts of included studies, displayed as choropleth maps generated in R (v 4.5.1; R Core Team, 2023) using the ggplot2 package. Frequency distributions summarized ecosystem-type representation and restoration approaches. Co-occurrence patterns between restoration techniques and ES categories were explored through cross-tabulations and visualized as stacked barplots and heatmaps. Cascading linkages among restoration approaches, ecosystem services, and policy scales were illustrated using Sankey diagrams implemented with the networkD3 package.

Policy integration was evaluated as the proportion of studies referencing policy instruments, separated by region, restoration technique, and policy type. We further assessed monitoring and evaluation practices as the share of studies reporting explicit indicators, grouped into performance metrics (e.g. oyster density, biodiversity indices, shoreline retreat), citizen-science contributions, and adaptive-management schemes.

A complete checklist of ROSES reporting items is provided in Table S2 (Supplementary Materials). This review complies with the ROSES 2022 checklist for systematic reviews (Haddaway et al., 2018), summarized in Table S2.

Results

Evidence base & publication trends

Our systematic search yielded 151 empirical studies published between 2000 and 2024 that explicitly evaluated ecosystem services associated with shellfish reefs, distributed across distinct regions worldwide (Fig. 1A). The production of evidence has increased markedly since 2010, coinciding with the global expansion of NbS frameworks and the implementation of coastal-management policies such as the EU Marine Strategy Framework Directive (MSFD) and the New Zealand Coastal Policy Statement (Fig. 1B).

The annual number of publications reveals a clear upward trend in both scientific attention and policy integration. Early studies (2000–2010) focused mainly on ecological processes and habitat restoration, with few explicit policy links (Fig. 1B). However, after 2015 the proportion of papers referencing policy or governance instruments grew steadily and represents nearly 20-30% of the literature after 2020. This shift indicates an increasing recognition of shellfish bed restoration as a decision-relevant NbS that contributes to water-quality improvement, biodiversity enhancement, and coastal protection.

Geographically, the evidence base for ES in shellfish restoration is highly uneven across regions (Fig. 1A). Research is dominated by North America—particularly the United States—followed by Oceania (mainly Australia and New Zealand) and parts of Western Europe. In contrast, Africa and Latin America contribute very few studies, revealing a pronounced geographic and socio-economic bias in the global distribution of empirical knowledge. This imbalance constrains the development of standardized indicators and limits the policy uptake of restoration practices in the Global South, where ecological and socio-economic opportunities for NbS implementation are substantial (Jordan & Fröhle, 2022).

While all identified studies address ES, 75% explicitly mention restoration or policy, demonstrating their centrality in the field (Fig. 1C). In contrast, monitoring (16%), stakeholder engagement (19%), and nature-based solutions (8%) remain peripheral themes, despite their critical importance for scaling and sustaining restoration outcomes. These gaps highlight a persistent disconnect between ecological research, governance frameworks, and social participation in shellfish restoration initiatives.

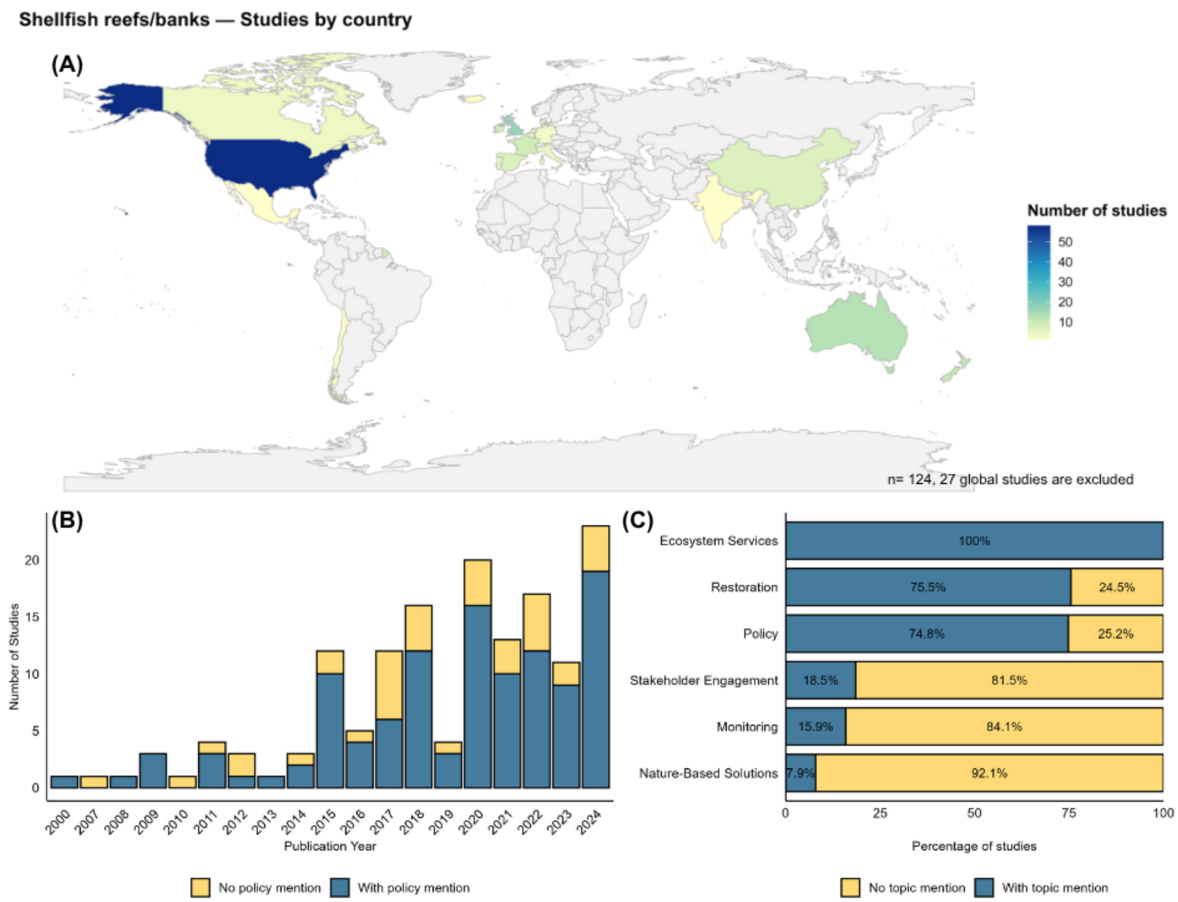

Figure 1. Global evidence base on ecosystem services from shellfish. (A) Geographic distribution of empirical studies evaluating ecosystem services (ES) provided by shellfish (n=127, 27 global studies are excluded). (B) Temporal trends in the number of published studies between 2000 and 2024, distinguishing those that explicitly reference policy or governance instruments (n=151). (C) Thematic coverage of reviewed studies showing the proportion mentioning key topics (n=151).

Among the 151 empirical studies analyzed, oyster reefs have dominated the global evidence base for more than 20 years, accounting for nearly 50% of all publications (Fig. 2A). These studies primarily focus on *Crassostrea virginica, Magallana gigas*, and *Ostrea* species, reflecting the prevalence of oyster-based restoration programs in temperate regions such as North America, Europe, and Oceania. Roughly one-fifth of the studies refer to "shellfish reefs" in general terms, without specifying taxa, while mussel (14%) and clam (8%) beds remain comparatively under-represented. Only a handful of studies address cockle or mixed bivalve systems, and virtually none target tropical or subtropical assemblages (Fig. 2B).

This imbalance underscores a strong taxonomic bias that mirrors global restoration funding and monitoring capacities, potentially constraining the understanding of underlying ecosystem functions and how different bivalve taxa contribute to ecosystem services such as nutrient cycling, sediment stabilization, or habitat provision. Expanding research beyond oyster-dominated systems would improve the representativeness of evidence and strengthen the design of shellfish nature-based solutions across diverse socio-ecological contexts.

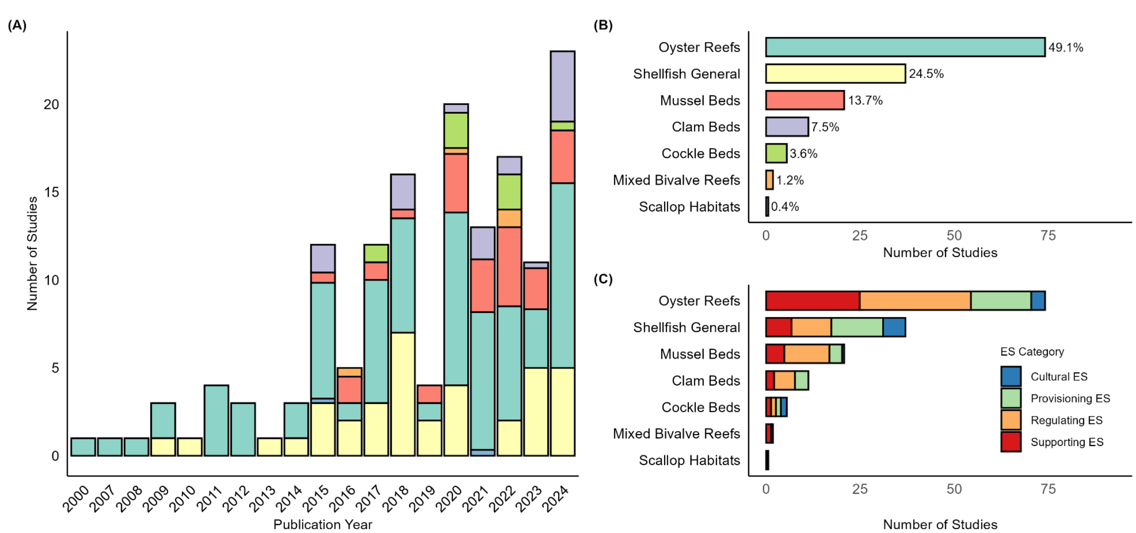

Figure 2. Temporal variations and taxonomic composition of the global evidence base on ecosystem services from shellfish (n = 151). (A) Annual number of studies by ecosystem type between 2000 and 2024. (B) Overall proportion of studies per ecosystem type.

Percentages denote the relative contribution of each habitat to the total evidence base. (C) Categories of ecosystem services addressed in each ecosystem type.

This taxonomic bias extends across the policy and restoration dimensions (Fig. 3). Oysters dominate the links to policy functions and focus (Fig. 3A-B), as well as the main restoration objectives, such as ecosystem function recovery, mainly linked to regulatory ecosystem services (Fig. 2C, Fig. 3D). Furthermore, the most common techniques —reef seeding and substrate addition— are overwhelmingly applied to oyster reefs, while other specific methods like pollution control, community engagement, and habitat protection are also addressed almost exclusively in oyster-dominated studies (Fig. 3C).

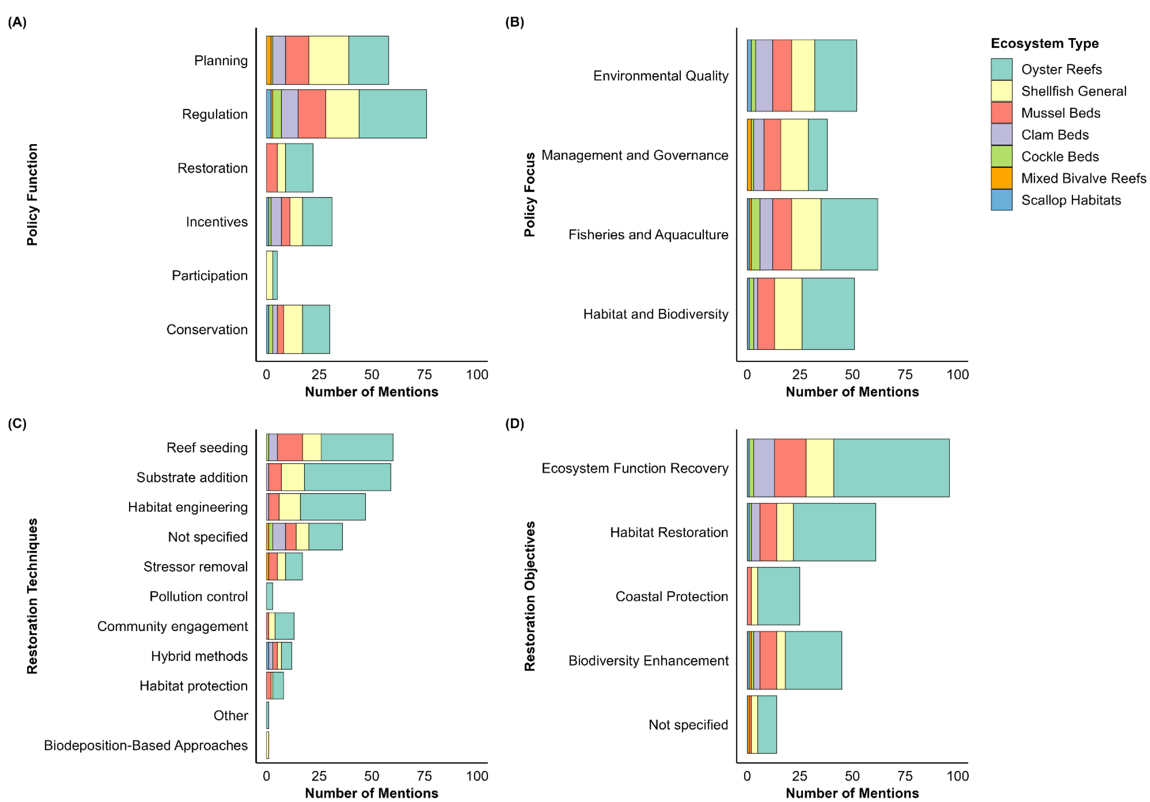

Figure 3. Distribution of restoration and policy dimensions across shellfish ecosystem types. (A) Policy functions, (B) Policy focus areas, (C) Restoration techniques, and (D)

Restoration objectives are reported in the reviewed literature. Panels A and B are based on the 113 studies addressing policy (75%), and panels C and D are based on the 114 studies addressing restoration (76%).

Ecosystem services

The number of studies addressing the ecosystem services of shellfish has grown sharply since 2010. Regulating and supporting services dominate throughout the record, while cultural and provisioning services appear more sporadically, showing modest increases only after 2018 (Fig. 4A, 4B). Most studies assess a single ES category, but multi-service approaches have become more common in recent years (Fig. 4C).

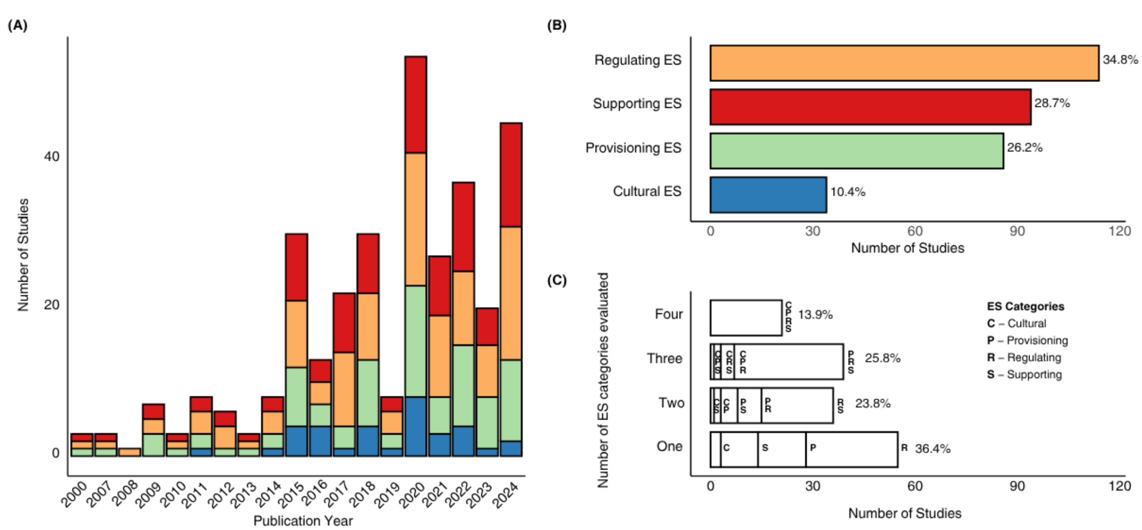

Figure 4. (A) Annual number of studies reporting each category of ecosystem services per year between 2000 and 2024 for coastal shellfish. (B) Overall proportion of studies per ecosystem service category. Percentages denote the relative contribution of each category

to the total evidence base. (C) Number and proportion of studies evaluating different combinations of Ecosystem Service (ES) categories. Percentages show the relative frequency for one to four categories, with letters indicating the specific ES categories present.

Regulating services—particularly water-quality improvement and coastal protection—were the most frequently addressed, reflecting the ecological importance and policy visibility of shellfish reefs as nature-based solutions for coastal resilience (Fig. 5). Supporting services such as habitat provision, biodiversity maintenance, and nutrient cycling were also widely addressed, often in combination with regulating services, emphasizing the dual role of shellfish habitats as ecosystem engineers and biodiversity enhancers (Fig. 4C, Fig. 5).

Provisioning services were less frequent and primarily associated with food provision derived from aquaculture and small-scale harvesting. Notably, aquaculture contexts accounted for 52 of the 151 studies analyzed (≈35%), exposing the dominance of production-oriented perspectives within the provisioning ES studies. Cultural services appeared only marginally and almost exclusively in studies involving community engagement or local-knowledge components, highlighting the dependence of cultural ES assessment on participatory and co-design approaches. This pattern shows that the social and relational values of shellfish ecosystems remain underexplored compared with their biophysical and economic dimensions.

The diversity of ES addressed also varied among all 151 studies. Most papers (36%) evaluated a single ES category, while a quarter (26%) considered three categories simultaneously, typically supporting, regulating, and provisioning. A smaller subset (14%)

examined all four ES categories together, reflecting integrative frameworks that link ecological functions with societal benefits (Fig. 4C). Over time, the inclusion of cultural and provisioning dimensions increased modestly, suggesting a gradual shift toward more holistic understandings of the multifunctionality of ecosystem services (Fig. 4A).

At the ecosystem level, oyster reefs dominate the ES literature, showing a clear prevalence of regulating services, a trend also mirrored in studies of mussel and clam beds. Other shellfish systems display a more balanced distribution over the ES categories. Notably, scallop and clam habitats lack cultural-service assessments, and scallop beds also lack regulating-service studies, revealing taxonomic and functional biases that limit cross-ecosystem comparability (Fig. 2C).

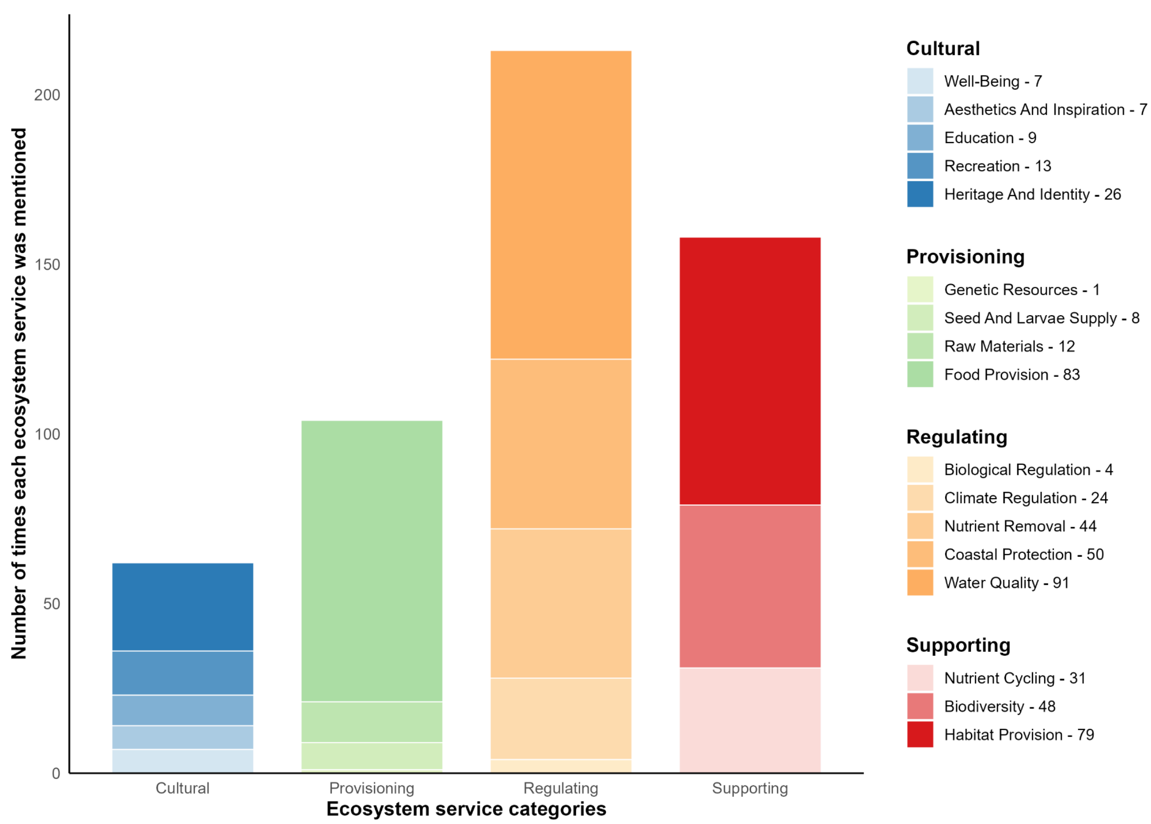

Figure 5. Frequency of ecosystem service categories and subcategories reported over the 151 studies included in the review. Bars show the total number of times each ecosystem service was mentioned. Subcategories are ordered by frequency within each category.

Restoration approaches and ecosystem service linkages

Of the 151 reviewed studies, 114 (76%) explicitly addressed restoration (Fig. 1C). Of these, active restoration was the dominant approach (64 studies), followed by hybrid approaches combining active and passive methods (17) and passive restoration (2). An additional 31 studies referred to restoration without specifying the method used (Fig. 6). The dominant methods were substrate addition, reef seeding, and habitat engineering, which together account for most interventions. These techniques are primarily aimed at restoring ecosystem functions, followed by habitat recovery, biodiversity enhancement, and coastal protection (Fig. S2). Passive approaches—such as stressor removal and habitat protection—were less frequent and typically focused on maintaining existing ecological integrity rather than initiating new processes.

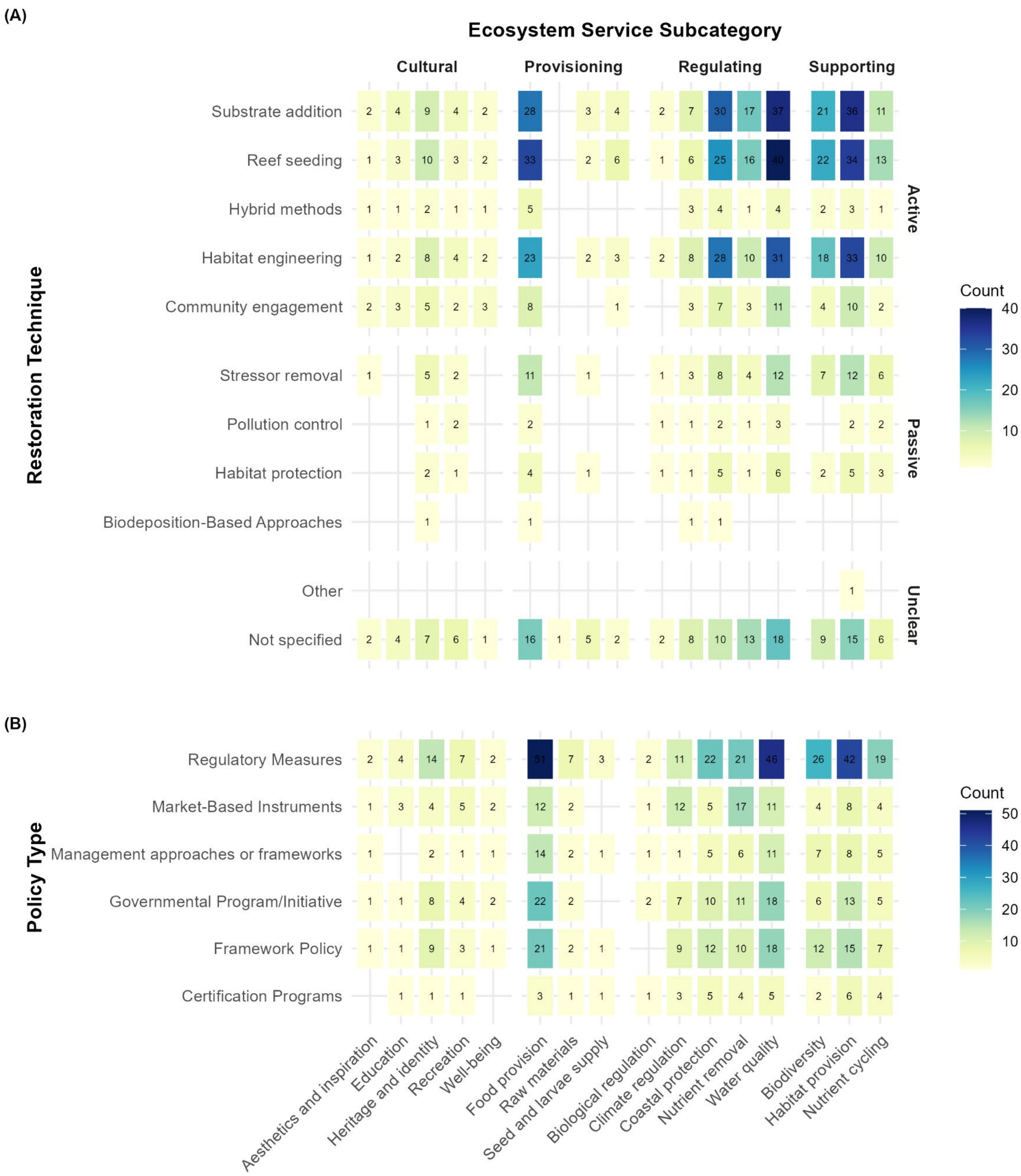

Figure 6. Heatmap showing the co-occurrence between specific (A) restoration techniques, and (B) Policy types (y-axis) with ecosystem service (ES) subcategories (x-axis). The columns are grouped into the four major ES categories—Cultural, Provisioning, Regulating, and Supporting—and the rows are grouped by restoration approach—Active,

Passive, Hybrid, or Unclear. Panel A is based on the 114 studies addressing restoration (76%), while Panel B is based on the 113 studies addressing policy (75%).

Across all restoration techniques, both regulating and supporting services—notably water-quality improvement, nutrient removal, habitat provision, and biodiversity maintenance—emerged as the most frequently quantified outcomes. Hybrid methods that combine ecological engineering and community engagement showed the strongest co-occurrence of ecological and social benefits, bridging restoration outcomes with policy visibility and societal participation (Fig. 7).

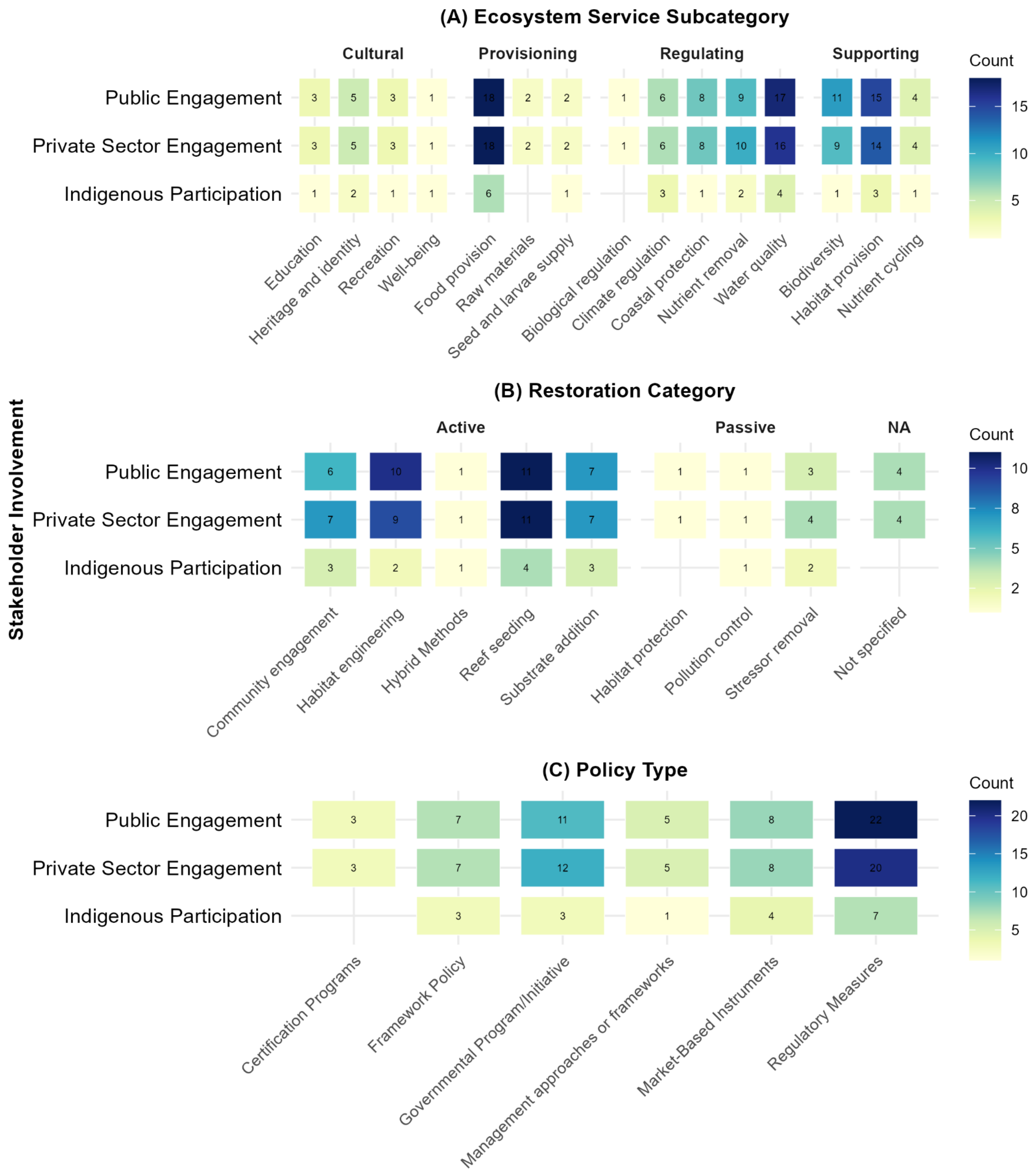

Figure 7. Heatmap showing the co-occurrence between *stakeholder participation per ecosystem services (A), restoration (B) and policy (C) categories*. Panels A and C are based on the 28 studies addressing stakeholder involvement (19%), while Panel B is based on the 21 studies addressing both stakeholders and restoration (14%).

Despite the overall expansion of reporting on restoration initiatives, monitoring of these initiatives remains weakly integrated: only 24 of the 114 restoration-focused studies (21%) reported explicit monitoring activities. Among these, the majority involved performance metrics (14 mentions), followed by citizen science initiatives (9) and adaptive management approaches (4). It is important to note that monitoring was recorded here as long-term observation of restoration outcomes rather than short-term measurements typically reported in active restoration studies. This limited emphasis on systematic evaluation underscores a major implementation gap between restoration practice and evidence-based assessment, which, when addressed, leads to improved practice.

Of the 151 studies, 114 addressed restoration (75.5%), 113 addressed policy (74.8%), and 76 studies (50%) addressed both simultaneously (Fig. 1C). These 76 studies form the triple-intersection subset used to map the linkages among restoration approaches, ecosystem-service (ES) categories, and policy focus areas. The Sankey diagram (Fig. 8) visualizes this subset, revealing 34 unique Restoration–Service–Policy combinations, each represented by a flow whose width is proportional to the number of studies supporting that linkage.

Within this subset, active restoration dominates (38 studies), followed by hybrid approaches (15) and passive restoration (2), while 21 studies mention restoration without specifying the method used. Across all restoration types, regulating services were most frequently assessed, followed by supporting and provisioning services, whereas cultural services were less represented.

These ES categories map onto four major policy domains: Fisheries and Aquaculture, Habitat and Biodiversity, Environmental Quality, and Management and Governance.

Among these, Fisheries and Aquaculture and Habitat and Biodiversity appear most frequently, while Environmental Quality and Management and Governance are less represented, providing a balanced view of how restoration outcomes intersect with policy priorities.

Dominant flows reveal strong associations between active and hybrid restoration and regulating and provisioning services, particularly under Fisheries and Aquaculture and Habitat and Biodiversity policies (Fig. 8). Supporting services connect mainly to biodiversity-focused objectives, while cultural services—although limited—span multiple policy areas, highlighting emerging socio-ecological and relational dimensions of shellfish NbS.

Collectively, this subset of 76 studies linking restoration, ecosystem services, and policy maintains the pattern observed in the full review remains of 151 studies, demonstrating that research primarily focuses on biophysical and production-oriented outcomes, while social and cultural contributions remain under-represented. This gap signals key opportunities for advancing more holistic, people- and nature-centered restoration strategies.

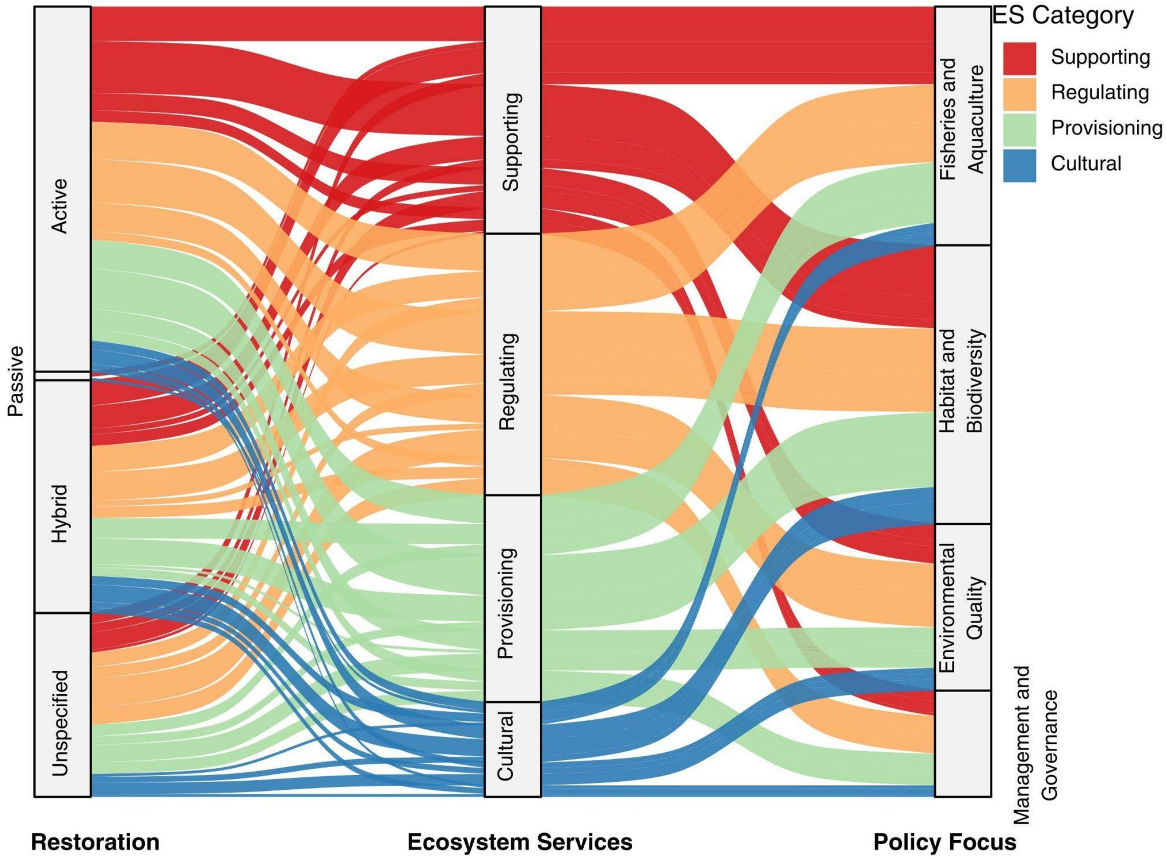

Figure 8. Sankey diagram showing the relationships among restoration approaches, ecosystem-service (ES) categories, and policy focus areas in shellfish nature-based solutions (NbS). The diagram summarizes evidence from 76 studies—the subset of the 151 reviewed studies that simultaneously address restoration, ES, and policy. These studies yield 34 unique Restoration–Service–Policy combinations, with flow widths proportional to the number of studies supporting each linkage.

Policy integration and governance patterns

The dominant policy type involves regulatory measures, followed by governmental programs, framework policies, and management approaches (Fig. 9A). Framework policies first appeared in 2011—linked to the Aichi Biodiversity Targets under the Convention on

Biological Diversity (CBD) and the UN Decade on Biodiversity —while market-based instruments gain prominence after 2020, reflecting an increasing use of economic mechanisms to operationalize ecosystem services in policy.

Market-based instruments are predominantly associated with regulating services —a focus also central to most restoration initiatives— (Fig. 9A-D), especially those related to nutrient reduction strategies and payments for ecosystem services (PES), which translate the nitrogen and phosphorus removal capacity of shellfish into tradable ecosystem benefits.

At the policy-function level, regulation remains the primary objective, followed by planning and incentives (Fig. 9C). Participation is comparatively under-represented, but has increased since 2020, particularly in Management and Governance, as have incentives in Environmental Quality. These patterns suggest a transition from normative, resource-control models toward adaptive, integrated governance emphasizing planning, incentive-based tools, and multi-stakeholder engagement.

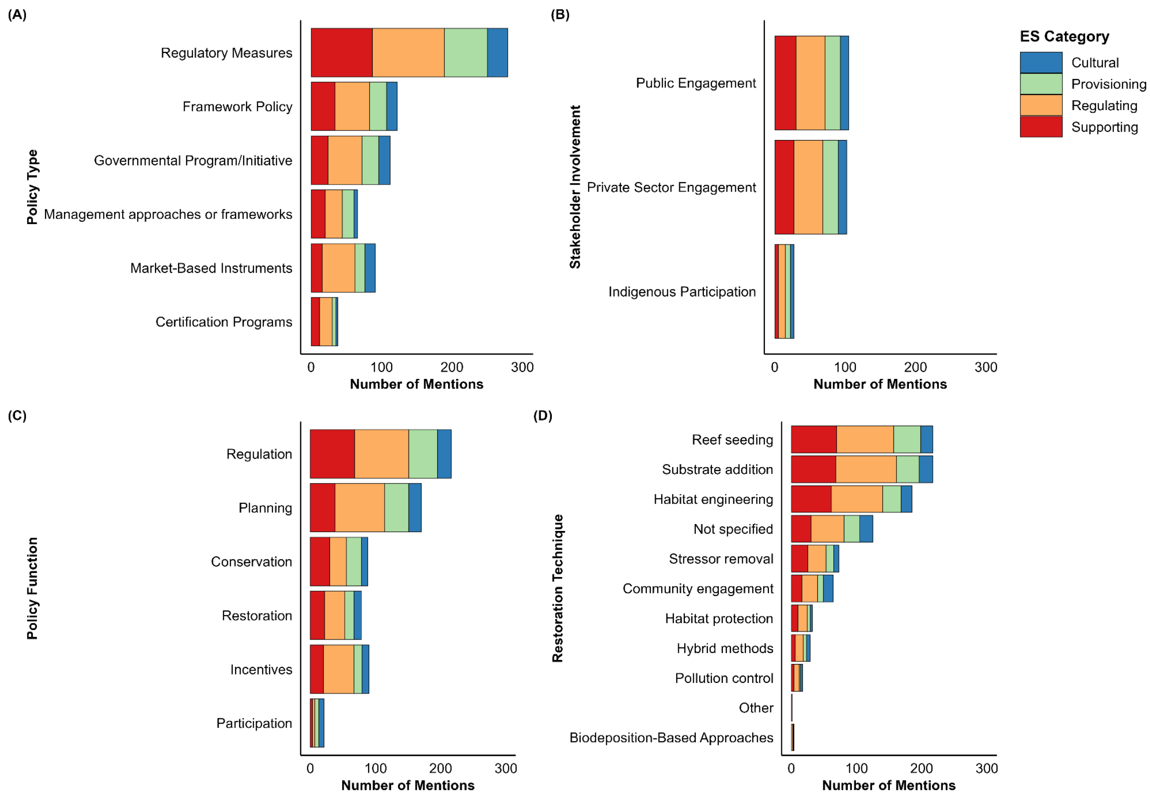

Figure 9. Four-panel stacked-bar figure showing Policy Type (A), Stakeholders (B), Policy Function (C), and Restoration Technique(D) by Ecosystem services category. Panels A and C are based on the 113 studies addressing policy (75%); panel B is based on the 28 studies addressing stakeholder involvement (19%); and panel D is based on the 114 studies addressing restoration (76%).

In terms of governance scales, local policies dominate, while regional frameworks—mainly from the EU—represent a smaller subset. International agreements appear after 2011, consistent with the expansion of global restoration and NbS initiatives. Thematically, the most frequent policy foci are Fisheries and Aquaculture, Habitat and Biodiversity, and Environmental Quality. Fisheries and aquaculture policies remain largely regulatory, reflecting a more traditional production-oriented perspective, whereas biodiversity and habitat policies exhibit greater diversity in instruments, combining regulation, planning, and incentives (Fig. S2).

Only 28 of 113 policy-related studies (26.5%) mention stakeholder participation, although nearly all emphasize its necessity for legitimacy and effectiveness. Engagement most often involves communities, governmental agencies, and the private sector, with Indigenous participation reported in fewer cases but consistently associated with co-management frameworks and recognition of traditional knowledge (Fig. 7, Fig. 9B).

NbS are mentioned in 12 studies (8%) (Fig. 1C), first appearing explicitly after 2018. Shellfish reefs are framed as NbS mainly for coastal protection, water-quality enhancement, and climate regulation, confirming their growing relevance within climate and sustainability agendas.

The temporal convergence of restoration, policy, and NbS mentions after 2018 indicates a conceptual and operational integration of these fields. The rise of incentive-based mechanisms and participatory governance frameworks after 2020 further points to a shift toward more socio-ecologically focused restoration models. Yet, persistent deficiencies in monitoring, participation, and incentive implementation suggest that institutional integration remains incomplete.

Discussion

In this section, we interpret our findings in relation to the four research questions. We discuss patterns of ecosystem-service delivery (RQ1) and their association with restoration approaches (RQ2), then identify major taxonomic, geographic, social, and institutional gaps

(RQ4), and finally examine policy instruments and governance mechanisms shaping the implementation of shellfish-based NbS (RQ3).

What we know: ecosystem-service delivery and restoration performance

This global synthesis confirms that shellfish consistently provide management-relevant ecosystem services—including water filtration, nutrient removal, habitat provision, and coastal protection—reinforcing findings from previous meta-analyses on the role of bivalves as biogenic ecosystem engineers (Van der Schatte Olivier et al., 2020). The evidence base is dominated by regulating and supporting services, indicating that restoration science continues to prioritize biophysical functions over provisioning and cultural dimensions, despite extensive literature showing the multiple ecological and social benefits of shellfish ecosystems (Coen et al., 2007; Needles et al., 2015). Cultural services appear mainly in studies with participatory or co-management approaches, highlighting the importance of integrating social and relational values into restoration assessments (Murray, 2016; Howie et al., 2024).

Active and hybrid restoration approaches dominate, mirroring global trends that emphasize engineered interventions and multi-technique designs. Their strong co-occurrence with policy visibility suggests that technical innovation gains traction only when interventions are institutionally grounded and socially supported (Murray et al., 2016; Stewart-Sinclair et al., 2020). Evidence from broader nature-based solutions research similarly shows that projects co-designed with communities deliver both ecological and governance benefits (Cubillo et al., 2023; Jordan & Föhle, 2022). Yet, only 21% of studies reported monitoring, and very few assessed policy outcomes, underscoring a persistent disconnect between ecological practice and decision-making needs.

A notable trend since 2020 is the emergence of market-based instruments—including nutrient-credit trading and payment for ecosystem services—that translate the regulating functions of shellfish into tradable units (Barrett et al., 2022; Fitzsimons et al., 2020; Petrolia et al., 2022; Rose et al., 2021). This reflects a broader shift toward more socio-ecologically oriented restoration models. However, persistent deficiencies in monitoring, stakeholder participation, and incentive implementation indicate that institutional integration remains incomplete. The effectiveness of these market mechanisms depends on credible ecosystem-service metrics and transparent accounting systems, which remain limited (Theuerkauf et al., 2022; Beck et al., 2011; NRC, 2010). Emerging certification schemes and living shoreline standards—design guidelines that define ecological, engineering, and performance criteria for nature-based coastal protection—represent early steps toward formalizing shellfish restoration within regulatory frameworks, but their coverage remains geographically and taxonomically narrow. Strong certification systems will be essential to attract private-sector engagement, paralleling the evolution of carbon and biodiversity credit markets (Farahmand et al., 2025).

Critical gaps: taxonomic, geographic, social, and institutional blind spots

Taxonomic and geographic biases are pronounced. The ecosystem-service evidence base is overwhelmingly concentrated in oyster-dominated systems from North America, Europe, and Oceania (zu Ermgassen et al., 2020; Beck et al., 2011). Mussel, clam, cockle, scallop, and mixed-bivalve habitats remain comparatively under-represented, with scallop and clam beds lacking cultural-service assessments entirely and scallop systems showing no regulating-service evaluations (Fig. 2C). These gaps create functional blind spots, limiting cross-ecosystem comparability and inflating the apparent dominance of oysters simply because they are the most studied, not necessarily because they deliver the broadest ecosystem service portfolios.

Tropical and subtropical regions remain largely unexamined, restricting our ability to test whether ecosystem-service outcomes documented in temperate environments generalize across different ecological, socio-cultural, and governance contexts.

Social and institutional gaps are equally significant. Monitoring is reported in only 21% of restoration studies, and stakeholder participation appears in just 27%—typically involving local communities, government agencies, or the private sector. Indigenous participation is even rarer, though consistently associated with co-management arrangements and the recognition of traditional knowledge. These omissions weaken our ability to understand when and why restoration gains institutional traction, how benefits are distributed, and how interventions interact with local knowledge systems and rights—factors that are critical for legitimacy, stewardship, and long-term project durability (Brown & Gabrys 2025). Although recent years show an emerging convergence between restoration, ES, and policy narratives, this integration remains largely conceptual rather than operational. Likewise, explicit NbS framing is still very limited (8%), constraining the alignment of shellfish restoration with broader climate, biodiversity, and sustainability agendas.

What to do differently: a global research agenda

Our synthesis identifies four research priorities to advance shellfish-based NbS:

- Integrate ecological engineering with community participation. Hybrid designs that couple substrate addition, reef seeding, or habitat engineering with community engagement yield the most diverse ecosystem-service portfolios and strongest policy resonance.
- Link ecological metrics to policy instruments. Translating ES—nutrient removal, shoreline protection, biodiversity enhancement—into indicators usable in environmental permitting, nutrient-credit markets, living-shoreline standards, or green-procurement schemes would improve policy uptake and comparability.
- Strengthen participatory and long-term monitoring. Monitoring frameworks including community-based and Indigenous-led protocols can bridge science, policy, and local stewardship and better capture relational outcomes.
- Develop credible, standardized ES metrics. Robust metrics underpin certification schemes capable of mobilizing business-sector investment and expanding restoration beyond existing hotspots.

Limitations and future directions

Our review draws on English-language, peer-reviewed literature and likely under-represents local knowledge, grey literature, and non-English sources. Heterogeneous reporting prevented quantitative effect-size comparisons across services. Future work should develop standardized monitoring templates, evaluate socio-ecological outcomes longitudinally, and examine how policy instruments shape restoration performance and equity.

Implications for practice and policy: an applied roadmap

Shellfish-based NbS can simultaneously advance biodiversity recovery, fisheries management, and water-quality regulation, but restoration remains uneven across taxa, regions, and policy designs. Building on our findings, we outline four priority actions to align restoration practice with national biodiversity and climate targets: (1) Establish outcome-based monitoring frameworks for ecological, social, and cultural indicators. (2) Embed ES evidence into policy instruments such as permitting, environmental standards, marine spatial planning, and PES/blue-carbon programs. (3) Expand restoration to under-represented taxa and regions, particularly in the Global South. (4) Strengthen governance and co-production, ensuring Indigenous participation, community rights, and durable stewardship pathways. Implementing these actions will enable governments, practitioners, and stakeholders to scale shellfish restoration as credible, equitable, and effective nature-based solutions that deliver durable benefits for people and ecosystems.

Conclusions

Shellfish reefs function as natural coastal infrastructure capable of delivering multiple, high-value ecosystem services while supporting biodiversity recovery. Our synthesis shows strong evidence for regulating and supporting services, and growing linkages between restoration actions, community participation, and policy uptake. Yet, persistent taxonomic, geographic, social, and institutional gaps—together with limited monitoring and sparse engagement of Indigenous and local knowledge systems—constrain the global scalability of shellfish-based Nature-based Solutions.

Addressing these gaps requires diversifying restoration across taxa and regions, strengthening participatory and long-term monitoring, and developing credible, standardized metrics that allow ecosystem-service outcomes to be embedded in policy and incentive mechanisms. Emerging tools such as nutrient-credit markets, certification schemes, and living-shoreline standards offer promising pathways but remain unevenly implemented.

Taken together, our results position shellfish restoration as a high-potential, but under-realized, socio-ecological opportunity. Advancing its contribution to coastal resilience and biodiversity goals will depend on integrating ecological evidence with governance innovation, equitable participation, and investment-ready performance metrics.

Author Contributions

María José Martínez-Harms conceived the idea, designed the study, conducted the initial title/abstract screening and applied inclusion/exclusion criteria, and led the writing of the manuscript; Uranía Lavín carried out the detailed full-text review, data extraction, and database curation; All authors verified coding consistency, resolved discrepancies collaboratively, contributed critically to manuscript drafts, and approved the final version.

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Conflict of Interest

The authors declare no conflict of interest.

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Supplementary Material

METHODS

Inclusion/Exclusion Criteria

Table S1. Inclusion and exclusion criteria for the systematic review of ecosystem services (ES) provided by shellfish banks. The table outlines the specific criteria used to evaluate studies based on relevance, methodology, scope, and policy significance, ensuring the inclusion of studies that focus on the socio-ecological and economic significance of shellfish ecosystems while excluding those that do not meet the set objectives.

Criterion	**Inclusion**	**Exclusion**
Topic Relevance	Studies evaluating specific **ecosystem services (ES)** of shellfish banks/reefs (*e.g., oysters, mussels, clams*).	Studies focusing on general marine ecosystems without specific reference to shellfish banks/reefs.
	Research addressing the **socio-ecological, economic, or environmental significance** of shellfish reefs.	Studies on aquaculture or fisheries with no link to ecosystem services of natural/restored shellfish banks.
	Studies identifying shellfish reefs as **nature-based solutions (NBS)** or contributors to ecosystem resilience.	Papers unrelated to ecosystem services, restoration, or conservation of shellfish banks.
Frameworks and Methodologies	Uses established ES classification frameworks (*MEA 2005, TEEB 2010*).	Papers without use of recognized frameworks for ES classification.
	Provides **quantitative or qualitative evidence** of ES (*e.g., economic valuation, biodiversity, water quality*).	Lacks empirical evidence or data-driven conclusions (*e.g., opinion pieces, speculative papers*).
Geographical Scope	Studies from **any region** with relevant socio-ecological or economic context.	None (unless region is irrelevant to shellfish ecosystem services).
Study Type	Peer-reviewed articles, systematic reviews, or reports providing **empirical data**.	Opinion pieces, editorials without specific data or analysis.

	Studies explicitly evaluating **specific ES** (*e.g., nutrient cycling, habitat provision, food provision*).	Studies with a generalized focus, lacking detailed or specific analysis of ES for shellfish banks.
Irrelevant Topics	Relevant to natural or restored **shellfish banks/reefs** and their **ecosystem services**.	Research focusing solely on non-bivalve ecosystems (*e.g., coral reefs, seagrasses, mangroves*).
Policy/Restoration Relevance	Discusses policy implications, restoration, or conservation measures for shellfish ecosystems.	No mention of policy recommendations, restoration, or conservation approaches.

*With the inclusion and exclusion analysis, they were reduced to 151 records.

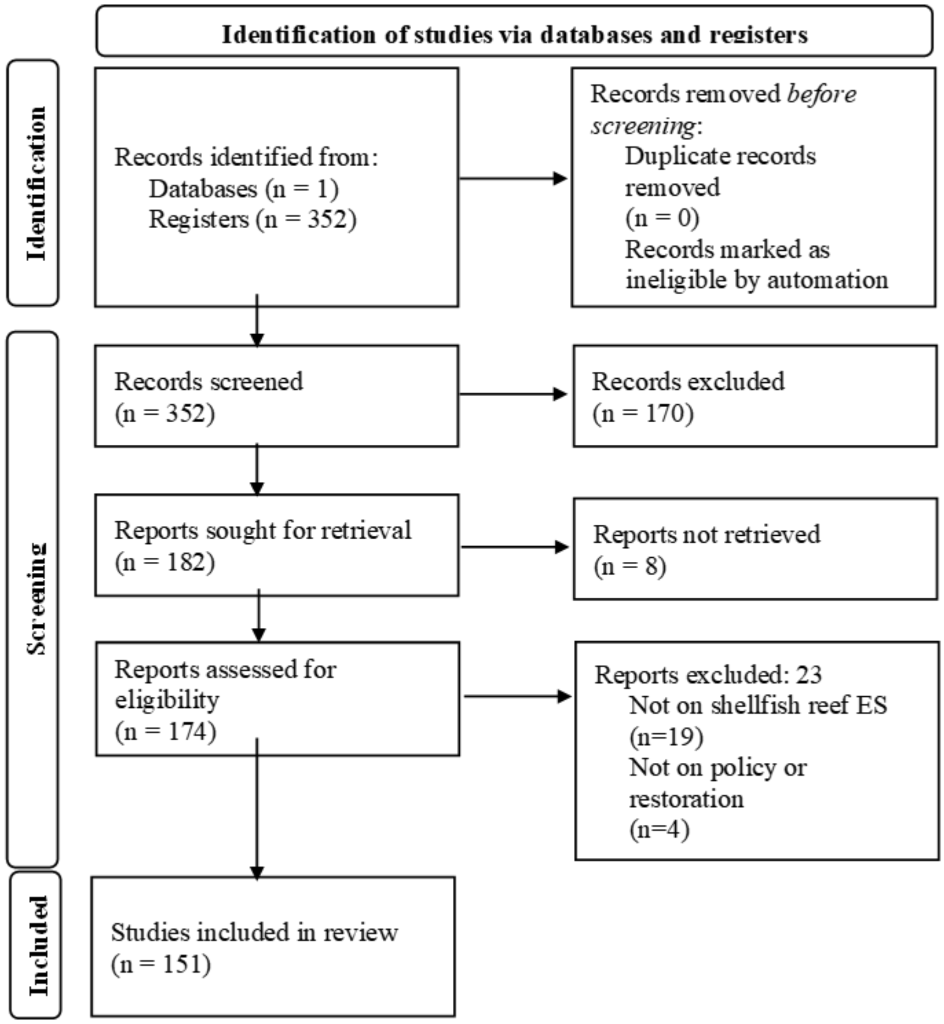
Table S2. ROSES summary table for the systematic evidence synthesis of ecosystem services provided by shellfish ecosystems

ROSES Element	Description (this review)
Title	*Ecosystem services and policy linkages in natural and restored shellfish ecosystems: a global systematic evidence synthesis*
Type of review	Systematic evidence synthesis (quantitative + qualitative)
Primary question	What types of ecosystem services are provided by natural and restored shellfish ecosystems, what restoration practices and policy instruments support them, and how are these patterns distributed globally?
Rationale	To synthesize empirical evidence on ecosystem services (ES) associated with shellfish reefs/banks and to examine how restoration practices and policy frameworks contribute to their delivery and recognition.
Frameworks used	Millennium Ecosystem Assessment (MEA 2005); TEEB 2010; IPBES 2018.
Search strategy	Web of Science Core Collection (all years ≤ Dec 2024). Search string: (“ecosystem service*” OR “ecological function*”) AND (“mollusk bank*” OR

	`“shellfish reef*” OR “bivalve bed*” OR “shellfish*”).`
Date of search	January 2025
Total records retrieved	352
Databases searched	Web of Science Core Collection (SCIE, SSCI, AHCI, ESCI)
Screening stages	(1) Title and abstract screening; (2) Full-text screening.
Screening tools	Manual screening in EndNote and Excel templates following ROSES workflow.
Inclusion criteria	Studies explicitly evaluating ES in natural/restored shellfish reefs/banks; use of recognized ES frameworks (MEA, TEEB, IPBES) or metrics; empirical evidence (quantitative or qualitative).
Exclusion criteria	Aquaculture-only focus; non-bivalve ecosystems (e.g., coral reefs, mangroves, seagrasses); non-empirical papers (e.g., opinions, conceptual essays). (Full details in Table S1).
Final sample size	151 studies retained after screening.
Data extraction fields	(1) Study context (year, country, scale, ecosystem type); (2) Ecosystem services (category, sub-services, metrics); (3) Restoration practices (approach, techniques, objectives, monitoring); (4) Policy variables (instrument type, scale, function, stakeholders).
Data synthesis methods	Descriptive and comparative analyses of temporal, geographic, and thematic patterns; visualizations via barplots, heatmaps, and Sankey diagrams (linking restoration–ES–policy).
Software used	R v 4.5.1 (R Core Team, 2023); packages tidyverse, ggplot2, networkD3.

Bias assessment	Transparent screening by two reviewers; standardized coding scheme.
Geographic coverage	Global – studies spanning > 90 countries across all continents (Fig. 2).
Outputs produced	Figures 1–9 (temporal trends, geographic distribution, ES frequencies, restoration approaches, policy integration); Tables S1–S5 (detailed metadata).
Limitations	Restriction to Web of Science may exclude grey literature; language bias possible (English-only search).
Data and code availability	All extracted datasets, metadata, and R scripts available at [repository DOI placeholder].
AI usage statement	No AI tools used for data extraction or analysis; AI assisted only in language editing per journal guidelines.
Reporting standard compliance	Complies with ROSES 2022 checklist for systematic reviews (Haddaway et al., 2018).

Figure S1. ROSES flow diagram



Spatial Scale

Table S3. Classification of spatial scales in the reviewed articles. The table presents the classification of spatial scales applied in the reviewed studies, based on the geographical extent considered in each analysis.

Spatial Scale	Definition
Local scale	Studies focused on site-specific or small-area assessments, typically limited to a single reef, bay, or community-level setting
Regional scale	Studies encompassing multiple sites or broader geographical units such as estuaries, coastal regions, or administrative areas

Global scale	Studies or reviews addressing international contexts, cross-regional comparisons, or global initiatives related to shellfish reef restoration (e.g., the Native Oyster Restoration Alliance, NORA)

Ecosystem Type

Table S4. Classification of Shellfish-Specific Ecosystems. This table categorizes shellfish-specific ecosystems based on dominant species and habitat type, including oyster reefs, mussel beds, clam beds, scallop habitats, cockle beds and mixed bivalve reefs. When no ecosystem type was specified, it was recorded as "shellfish general". It provides a framework to systematically evaluate ecosystem services, restoration practices, and policy relevance for each ecosystem type.

Ecosystem Type	**Subcategory**	**Description**
Oyster Reefs	Crassostrea (Eastern oyster reefs)	Reefs formed by Crassostrea species, e.g., *Crassostrea virginica* (Eastern oyster).
	Ostrea (Native European oysters)	Reefs formed by *Ostrea* species, e.g., *Ostrea edulis* (European flat oyster).
Mussel Beds	Mytilus (Blue mussel beds)	Beds dominated by *Mytilus* species, e.g., *Mytilus edulis* (blue mussel).
	Perna (Green-lipped mussel beds)	Beds dominated by *Perna canaliculus* (green-lipped mussels).
Clam Beds	Hard clam beds	Habitats with dense populations of hard clams, e.g., *Mercenaria mercenaria*.
	Geoduck clam habitats	Habitats dominated by geoduck clams, e.g., *Panopea generosa*.
Scallop Habitats		Habitats where scallops, e.g., *Pecten maximus*, form dense aggregations.
Cockle Beds		Habitats dominated by dense populations of cockles (family Cardiidae), e.g., *Cerastoderma edule* (common cockle).
Mixed Bivalve Reefs		Shellfish habitats featuring multiple bivalve species coexisting.

Ecosystem Services

Table S5. Overview of the ecosystem services classification and grouping applied in the systematic review.The table presents the classification of ecosystem services following the Millennium Ecosystem Assessment (MEA, 2005) framework and the grouping of each service recorded across the 151 reviewed studies.

ES Category	ES grouped	Specific ES mentioned
Supporting	Biodiversity	biodiversity, biodiversity support, ecological carrying capacity, energy transfer between trophic levels, food web support, food web structure, maintaining nursery populations, nursery, provisioning nutritionally valuable prey.
	Habitat provision	bioengineering, ecosystem engineering, foraging habitat, habitat complexity, habitat creation, habitat enhancement, habitat formation, habitat provision, habitat provisioning, habitat heterogeneity, landscape and habitat diversity.
	Nutrient cycling	benthic–pelagic coupling, biogeochemical cycling, enhancement of productivity, nitrogen regeneration/excretion, nutrient cycling, nutrient regeneration, perturbation and alteration of sediment properties, primary production, sediment biogeochemistry alterations.
Regulating	Water quality	heavy metal absorption, pollutant removal, removal of contaminants, sediment stabilization, toxin removal, turbidity reduction, water clarification, water clarity, water filtration, water purification, water quality
	Nutrient removal	biodeposition, burial of biologically important element, denitrification, eutrophication control, eutrophication mitigation, nitrogen cycling, nitrogen removal, nutrient removal, nutrient uptake, phosphorus removal, reduced risk of eutrophication, sequestration of nitrogen, seston depletion.
	Coastal protection	coastal protection, coastal resilience, erosion control, erosion protection, flood protection, mitigation debris movement, mitigation of storm surge, reduced erosion, shoreline erosion prevention, shoreline erosion reductions, shoreline protection, shoreline stabilization, stabilize foreshores, stabilizing shorelines, storm surge protection, vertical accretion, wave energy dissipation
	Climate regulation	carbon removal, carbon sequestration, climate change mitigation, climate regulation, sequestration of carbon
	Biological regulation	biological control prevention, disease regulation, pathogen removal, removal pathogens
Provisioning	Food provision	food provision, food production, provision of food, food provide, food sources, fisheries, seafood, seafood supply, seafood production, production of harvested species, aquaculture, wild animals for nutrition, bivalve harvest, bivalve fisheries, shellfish for food, shellfish meat, fishery

		output, clam production, fish production, fish productivity, shell fishing, oyster harvest, seafood industries, commercial fishery, shellfish harvests, food security, mariculture, meat
	Seed and larvae supply	brood stock oyster population enhancement, shellfish seeds, shellfish larvae, spat, shellfish spat
	Raw materials	provision of material, shell, shell extraction, shell production, ornamental materials, ornaments, shell by-products, poultry grit, construction material, mineral resource, shell substrate, building materials, jewelry, shell aggregate
	Genetic resources	genetic resources
Cultural	Recreation	adventure, challenge, ecotourism, food tourism, leisure, recreational fishing, recreational harvesting, recreation, tourism
	Aesthetics and inspiration	aesthetic appeal, aesthetic appreciation, biodiversity appreciation, freedom, inspiration, ornamental use
	Heritage and Identity	bequest value, contribution to community, culture, cultural activities, cultural continuity of traditional food gathering, cultural heritage, cultural practices, cultural services, cultural shellfish gathering, cultural symbology, cultural value, cultural value of biodiversity, existence value, family heritage, harvesting culturally valued food species, harvesting traditions, heritage, historical harvest, identity, indigenous and colonial use, local history, non-commercial family harvesting, past experiences, responsibility of care – environment, responsibility of care – husbandry, responsibility of care/bequest, sense of attachment to nature, sense of place, spiritual and religious, spiritual and symbolic, spiritual experience heritage, spiritualism, symbolic meaning, symbolic values
	Education	art, educational use, intellectual valor, knowledge, public awareness, research, science, scientific research, skills
	Well-being	well-being, community engagement, independence, job satisfaction, lifestyle, mental health, physical health, pride, relationship with nature, safety, security, security and reliability, sense of belonging, sense of pride, sense of purpose, shared experiences, social bonds, social capital, therapy, transformation, livelihoods

Country	**Country**	**Country**	**Country**
Angola	Estonia	Laos	Russia
Antarctica	Ethiopia	Latvia	Rwanda
Argentina	Fiji	Lithuania	Scotland
Australia	Finland	Madagascar	Senegal
Austria	France	Malawi	Seychelles
Bangladesh	Gaza Strip	Malaysia	Singapore
Barbados	Germany	Mali	Slovakia
Belarus	Ghana	Malta	Slovenia
Belgium	Global	Mexico	Solomon Islands
Belize	Greece	Mongolia	South Africa
Benin	Guatemala	Morocco	South Korea
Bolivia	Hungary	Mozambique	Spain
Botswana	Iceland	Namibia	Sri Lanka
Brazil	India	Nepal	Sudan
Brunei	Indonesia	Netherlands	Sweden

Bulgaria	Iran	New Zealand	Switzerland
Burkina Faso	Ireland	Nicaragua	Taiwan
Burundi	Israel	Nigeria	Tanzania
Cambodia	Italy	Norway	Thailand
Cameroon	Jamaica	Oman	Tunisia
Canada	Japan	Pakistan	Turkey
Chile	Jordan	Panama	Uganda
China	Kazakhstan	Papua New Guinea	Ukraine
Colombia	Kenya	Paraguay	United Kingdom
Costa Rica	Laos	Peru	United States
Croatia	Latvia	Philippines	Uruguay
Czech Republic	Lithuania	Poland	Uzbekistan
Democratic Republic of Congo	Madagascar	Portugal	Vietnam
Denmark	Malawi	Puerto Rico	Wales
Ecuador	Malaysia	Russia	Zambia
Egypt	Mali	Rwanda	

Restoration

Table S6. Overview of the restoration classification scheme applied in the systematic review. The table presents the categories and operational definitions used to classify restoration-related aspects, including restoration objectives, approaches, specific restoration categories, and monitoring practices reported in the reviewed literature.

Characteristics of the Restoration	Category	Definition
Restoration Objectives	Habitat Restoration	Restoration focused on recreating or enhancing natural shellfish habitats (e.g., oyster reefs, mussel beds).
	Biodiversity Enhancement	Efforts aimed at improving species richness and abundance in restored habitats.
	Ecosystem Function Recovery	Targeting restoration of key ecosystem services (e.g., water filtration, nutrient cycling).
	Coastal Protection	Projects designed to use shellfish banks as natural breakwaters to reduce coastal erosion and storm impacts.
Restoration Approach	Passive	Natural recovery processes occur without direct human intervention, relying on the removal of stressors or protection measures.
	Active	Direct human actions are implemented to accelerate or enhance ecosystem recovery (e.g., substrate addition, species reintroduction, or habitat engineering).
	Hybrid	Combination of passive and active strategies, where initial interventions support or complement natural recovery processes.
Specific Restoration Category	Substrate addition	Deploying hard and heterogeneous substrates (e.g., cultch, shells, rocks, artificial reefs) to promote shellfish settlement and growth.
	Reef seeding	Introducing juvenile shellfish or larvae to establish or enhance populations. (e.g., adding spat or larvae)

	Habitat engineering	Modifying physical or hydrological conditions (e.g., altering flow, sediment, or shoreline structures) to create suitable conditions for restoration.
	Community engagement	Active participation of local communities in the design, monitoring, and implementation of restoration (e.g., participatory restoration programs)
	Hybrid Methods	Combining natural and engineered approaches (e.g., co-deployment of seagrass and oyster reefs for mutual benefits).
	Stressor removal	Reduction or elimination of pressures limiting natural recovery (e.g., fishing restrictions)
	Habitat protection	Safeguarding existing habitats to enable natural regeneration (e.g., MPAs)
	Pollution control	Reducing nutrient or contaminant inputs to improve environmental conditions. (e.g., reducing nutrient runoff)
	Biodeposition-Based Approaches	Using shellfish biodeposits to enhance sediment organic content and promote habitat growth. Biodeposition approaches primarily rely on natural processes (e.g., the natural filtration and deposition of organic material by shellfish) to enhance sediment organic content and promote habitat growth.
Monitoring	Performance Metrics	Defining and measuring success through biological (e.g., shellfish density), ecological (e.g., biodiversity), and socio-economic indicators.
	Adaptive Management	Implementing flexible strategies informed by ongoing monitoring results.
	Citizen Science	Engagement of local communities and volunteers in monitoring and restoration activities.

Nature-Based Solutions

Table S7. Classification of Nature-Based Solutions (NbS) types applied to shellfish beds. The table presents the classification of NbS types in which shellfish beds were discussed as nature-based solutions for climate mitigation or resilience building.

Natura-Based Solutions	Definition
Climate Mitigation	Using shellfish reefs to sequester carbon and mitigate ocean acidification through biogenic calcification and habitat enhancement
Coastal Protection	Increasing coastal resilience to environmental changes, including sea-level rise, erosion, and storm impacts, through the physical structure and wave attenuation capacity of reefs.
Water Quality	Improvement of water conditions through the filtration capacity of shellfish and associated biogeochemical processes.
Remove Nutrients	Reduction of nutrient loads (e.g., nitrogen, phosphorus) from the water column via biofiltration and biodeposition processes

Policy

Table S8. Overview of the policy classification scheme applied in the systematic review. The table presents the categories and operational definitions used to categorize policies according to their thematic focus (policy area), primary function or objective, and type of policy instrument mentioned in the reviewed literature.

Characteristics of the Policy	Category	Definition
Type of Policy Instrument	Regulatory Measures	Laws and regulations protecting shellfish habitats (e.g., marine protected areas, harvesting restrictions).
	Market-Based Instruments	Incentives like tax breaks or subsidies for restoration and conservation projects.
	Certification Programs	Ecosystem service certification or eco-labels (e.g., for sustainable fisheries or aquaculture practices).
	Governmental Program/Initiative	Strategic initiatives and plans for the management and/or restoration of ecosystems, resources, or productive sectors promoted by local governments. (e.g., species management plans, restoration plans, National Shellfish Initiative (EE.UU.))

	Framework Policy	Policy that defines broad principles, goals, and guidelines to guide and coordinate the actions of governments, institutions, and actors. (e.g., United Nations Decade on Ecosystem Restoration, EU Biodiversity Strategy for 2030, Kunming–Montréal Global Biodiversity Framework)
	Management approaches or frameworks	Integrated approaches and tools guiding the sustainable use and governance of marine and coastal resources (e.g., Marine spatial planning (MSP), ecosystem-based management (EBM))
Policy Frameworks	International Agreements	Global agreements like the Convention on Biological Diversity (CBD) or IPBES (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services).
	Regional Policies	Policies specific to regions, such as EU Marine Strategy Framework Directive or U.S. Clean Water Act.
	Local Legislation	Community-driven policy initiatives or state-level regulations targeting restoration.
Thematic Area (Policy Focus)	Fisheries and Aquaculture	Policies on resource use and sustainability, including aquaculture leases, fishing quotas, and food safety regulations.
	Habitat and Biodiversity	Instruments for habitat and species conservation, such as MPAs, restoration programs, and biodiversity protection frameworks.
	Environmental Quality	Policies ensuring ecosystem integrity through water quality standards, nutrient control, and pollution or emission regulations.
	Management and Governance	Integrated approaches for marine and coastal management, including Marine Spatial Planning (MSP), Integrated Coastal Zone Management (ICZM), Ecosystem-Based Management (EBM), and community or indigenous governance.

Policy Function (Objective/Purpose)	Conservation	Policies aimed at maintaining or protecting ecosystems, species, or ecological functions from degradation or loss.
	Restoration	Policies designed to recover or enhance degraded habitats and ecosystem services through active or passive measures.
	Regulation	Legal or administrative mechanisms establishing rules, standards, or restrictions to control human activities and resource use.
	Incentives	Economic or social instruments (e.g., subsidies, compensation schemes, market mechanisms) that promote sustainable practices or conservation actions.
	Planning	Strategic and spatial frameworks guiding the allocation, management, and use of coastal and marine resources (e.g., MSP, ICZM).
	Participation	Mechanisms that involve stakeholders and communities in decision-making, governance, and implementation processes.
Stakeholder Involvement	Public Engagement	Mechanisms for including citizens, NGOs, and communities in policy formulation.
	Private Sector Engagement	Encouraging industries (e.g., fisheries, tourism) to invest in restoration and sustainable practices
	Indigenous Participation	Recognizing and incorporating Indigenous knowledge and rights in conservation efforts
Engagement Methods	Public Consultation	Mechanisms to collect opinions and feedback from stakeholders or the public. Engagement is mainly consultative, and input informs but does not determine decisions. (e.g., public consultation processes, oral hearings, appeals processes, expert panels, interviews)
	Participatory Interaction	Two-way processes that foster dialogue, learning, and collaboration among stakeholders, helping refine policies and integrate diverse knowledge. (e.g., workshops, stakeholder committees, early

		engagement, community relationship-building)
	Co-management	Collaborative and power-sharing arrangements where stakeholders jointly design, implement, and/or manage initiatives. (e.g., co-development of management goals and schemes, partnerships, citizen science programs, cooperative fishery management)

RESULTS

Figure S2. Summary of the relationships among policy aspects, restoration approaches, and participation methods in the reviewed articles: (A) Policy functions by policy focus, (B) Restoration techniques by restoration objectives, (C) Policy focus by policy frameworks, and (D) Engagement methods by stakeholder involvement.