

Mapping actor diversity is essential for advancing global seagrass conservation

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SUMMARY

Seagrass conservation is increasingly organised around global agendas for protection, restoration, climate mitigation, biodiversity recovery and nature-positive finance. The actor systems that determine whether these agendas succeed remain poorly described, if at all. We developed a heuristic actor-centred framework for seagrass social-ecological systems, combining a literature scan with expert-informed scoring of 22 actor profiles across nine attributes. Actor-relevant seagrass research was concentrated around governance, pressure and dependent actors, while intervention and finance actors were rarely foregrounded. More importantly, material leverage, literature visibility and accountability were misaligned. Several actors with high capacity to shape seagrass outcomes, including fisheries managers, donors, government agencies, and commercial fisheries actors, were less visible than their potential influence suggests. We identify recurrent authority-dependence, impact-visibility and finance-accountability asymmetries that reveal hidden leverage points for conservation. Seagrass conservation must move beyond generic stakeholder language towards actor mapping that links ecological recovery with authority, incentives, legitimacy, knowledge and accountability.

INTRODUCTION

Conservation is increasingly understood as a problem of governing relationships among ecosystems, people and institutions. Social-ecological systems theory shows that most environmental outcomes emerge from interactions among resource systems, resource users, governance arrangements, and broader social and economic context.¹ Similarly, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) moves conservation beyond a focus on ecological stocks and flows towards the diverse values, institutions and decisions through which nature becomes meaningful, contested and governed.^{2,3} Across conservation contexts, this shift has placed actors, their roles, and their relationships with ecosystems at the centre of explaining environmental outcomes.⁴⁻⁶

Inclusion of diverse actors is recognized as central to the achievement of equitable and effective conservation and management. Local actors are not peripheral stakeholders to be consulted after ecological priorities are set but are part of the system through which conservation and management problems are defined, interventions are chosen and outcomes are produced.⁷ In small-scale fisheries, policies that treat small-scale actors as homogeneous can miss the diversity of assets, markets, institutions, access arrangements and livelihood strategies that underpin blue food systems.⁸ Marine social science makes a similar case for ocean governance, where equity, recognition, rights, inclusion and justice shape which actors benefit from conservation and development interventions.^{9,10} Patterns of social and cultural practices are increasingly understood as central to ocean governance,¹¹⁻¹⁴ and participatory research methods are an effective means of bringing social and ecological information to light.^{15,16} Research with Indigenous Peoples, and local communities, has shown that participation is not a single condition, but a continuum of roles, rights, influence and authority that shape social and ecological outcomes.⁵ These arguments mark a wider shift in conservation science and practice with an increasing recognition of the inseparability of humans and nature and the complexity of their relations.^{17,18}

Seagrass meadows have just started to receive attention in research on participation of diverse actors in conservation. Increasingly, they are visible in global policy and discussions about biodiversity and climate mitigation,¹⁹⁻²¹ reflecting a major increase in their charisma due to advances in ecological knowledge.²² Seagrass science has mapped global distributions,²³ documented decline and recovery trends,²⁴ quantified carbon stocks,²⁵ described ecosystem services,²⁶ assessed threats,²⁷ and developed restoration methods across a growing range of species and settings.²⁸ In practice, the field has become increasingly sophisticated in describing seagrass meadows but remains far less developed in describing the actors, values, and institutions that shape their futures.

Broadly, this is a conceptual limitation in how seagrass conservation is framed. Within science, policy and the media, seagrass meadows are commonly represented as carbon sinks to preserve, biodiversity features to protect, or ecosystems to restore. These framings have helped make seagrass legible to policy, climate finance and restoration agendas,^{20,29,30} but they also narrow the field of view. These framings a) obscure who governs coastal access, b) obscure values, rights, claims and benefit-sharing, c) obscure the social and institutional conditions that determine whether conservation and restoration are successful, and d) identify pressures without identifying the actors and incentives that produce them.

Seagrass conservation is therefore not only a question of meadow assets and condition, but also a question of social and institutional context. The dependencies, values, roles, actions, and positions of diverse actors is of relevance to whether and how seagrass is conserved or managed. This is because the people and institutions connected to seagrass ('actors') differ in how they depend on meadows, how they affect ecological processes, how much authority they hold, what knowledge they produce, what finance they control, how visible they are, and whether they are accountable for outcomes. These differences are often obscured when diverse actors are grouped under the generic umbrella of "stakeholders."^{31,32}

Conservation actions and outcomes are shaped by asymmetries among actors. Those with the deepest dependence on seagrass may have limited visibility as resource users,³³ which may limit their authority over coastal decisions, while those with the greatest influence over water quality, coastal infrastructure or finance may not recognise themselves as seagrass actors. Furthermore, the influence of similar kinds of actors may vary spatially, such as farmers next to watercourses, or fishers whose grounds correspond more closely with seagrass. In addition, those able to shape narratives, public attention or funding priorities may have limited accountability for long-term ecological persistence or local benefit. These mismatches in influence, accountability and recognition are not secondary to seagrass conservation. Rather, they may help explain why ecological knowledge does not always translate into durable, equitable or effective action.

Despite the high proximity of human populations to seagrass meadows,³⁴ there has been limited attention to understanding and mapping the diverse actors who can shape seagrass conservation. Seagrass conservation needs this stronger social-ecological science approach. It is important to understand not just who actors associated with seagrass are, but also to characterize their diverse profiles, levels of influence, and asymmetries in shaping conservation actions and outcomes. Drawing on social-ecological systems theory,¹

stakeholder salience theory,³² conservation planning and protected area research,^{4,12} social equity and blue economy research,^{9,35} and actor-profile approaches from aquatic food systems,⁸ here we map the diverse actors who shape global seagrass conservation. We use actor profiles as analytical tools to identify the recurring social-ecological attributes that determines who governs, pressures, restores, finances, studies, narrates and ultimately shapes global seagrass futures.

RESULTS

A six-actor family framework for seagrass social-ecological systems

We defined six actor families that recur across seagrass social-ecological systems, informed by both prior literature, and practical experience working with these systems: dependent actors, pressure actors, intervention actors, governance actors, finance actors, and knowledge and agenda-setting actors (Table 1). Broadly, these actor families describe different positions within seagrass conservation rather than fixed stakeholder identities, and certain actors may occupy multiple positions at once. For example, a fisher may also be a citizen scientist, a restoration volunteer or a customary governance actor, a conservation NGO may produce knowledge, implement restoration, mobilise finance and influence policy, and a government agency may regulate, fund, monitor and narrate conservation.

The framework is therefore intended to reveal the actor's central position, not provide an exhaustive census of all seagrass actors. Specifically, it captures distinct ways in which societies and institutions depend on seagrass, affect seagrass condition, govern access and rules, finance action, implement interventions, produce knowledge and shape public or policy narratives.

Actor-relevant seagrass literature is fragmented across themes and pathways

To examine how these actor families appear in seagrass research, we conducted a broad literature scan on Web of Science using seagrass terms combined with actor-oriented terms (see Methods). We applied conservative title-and-abstract coding to identify records with clear actor relevance, their primary actor theme and their primary conservation pathway. This scan was not designed as a systematic review, but as a literature mapping exercise to understand how actor language is used and distributed across seagrass research.

Of the 2,839 records screened, 1,129 were classified as actor-relevant, 1,067 as partially actor-relevant and 643 as not actor-relevant. Within the actor-relevant literature, governance actors were the most frequently identified theme (n = 478), followed by pressure actors (n = 364) and dependent actors (n = 179). Knowledge and agenda-setting actors were less

common (n = 67), while intervention actors (n = 21) and finance actors (n = 20) were rarely the primary actor theme. This does not mean intervention and finance actors are unimportant; rather, it suggests they are rarely foregrounded as primary actors in seagrass research. The actor-relevant literature included articles on themes such as stakeholder perceptions and ecosystem services,^{36,37} tourism and recreation,³⁸ governance and policy barriers,^{39,40} Indigenous and collaborative restoration practice,⁴¹ local knowledge and participatory mapping,⁴² data systems and monitoring,^{43,44} blue carbon and finance,^{45,46} and restoration implementation barriers.⁴⁷

Conservation pathways were defined as the main social-ecological process through which actors were linked to seagrass conservation, degradation, recovery or governance. Whereas actor themes identify the primary actor position foregrounded in a record, pathways identify the mechanism or domain of action. The coded conservation pathways were similarly uneven. Governance and policy was the most frequent pathway (n = 246), followed by fisheries and food systems (n = 226), knowledge and monitoring (n = 118), coastal development and spatial planning (n = 107), tourism and recreation (n = 99), water quality and catchment management (n = 97), protection and marine protected areas (n = 88), restoration and recovery (n = 79), rights and equity (n = 39), and blue carbon and finance (n = 30).

This distribution shows that social dimensions of seagrass conservation are broadly recognised but remain biased towards certain actor themes and conservation pathways. The literature is most prevalent around governance, pressure and resource-use relationships, while intervention and finance actors are much less visible as primary actor themes. This pattern supports the need for a broader actor-centred framework.

Expert-informed scoring reveals distinct actor profiles

We scored 22 actor profiles across nine diagnostic attributes: dependence, direct pressure or impact, governance authority, financial influence, knowledge contribution, capacity to alter outcomes, narrative influence, accountability and visibility in seagrass policy or science (Figure 1; Table 2). These attributes draw on social-ecological systems theory, stakeholder salience and participation research, conservation power analysis, ocean equity research and actor-profile approaches in aquatic food systems.^{1,8,9,32,48} The resulting analytical framework encompassing 9 attributes of actors relevant to seagrass conservation is heuristic and simplifies actor diversity enough to support comparison, while retaining the social-ecological complexity needed for conservation planning. Thirty-five individuals completed the scoring activity gathering expertise across wide ranging disciplines and sectors related to seagrass conservation globally.

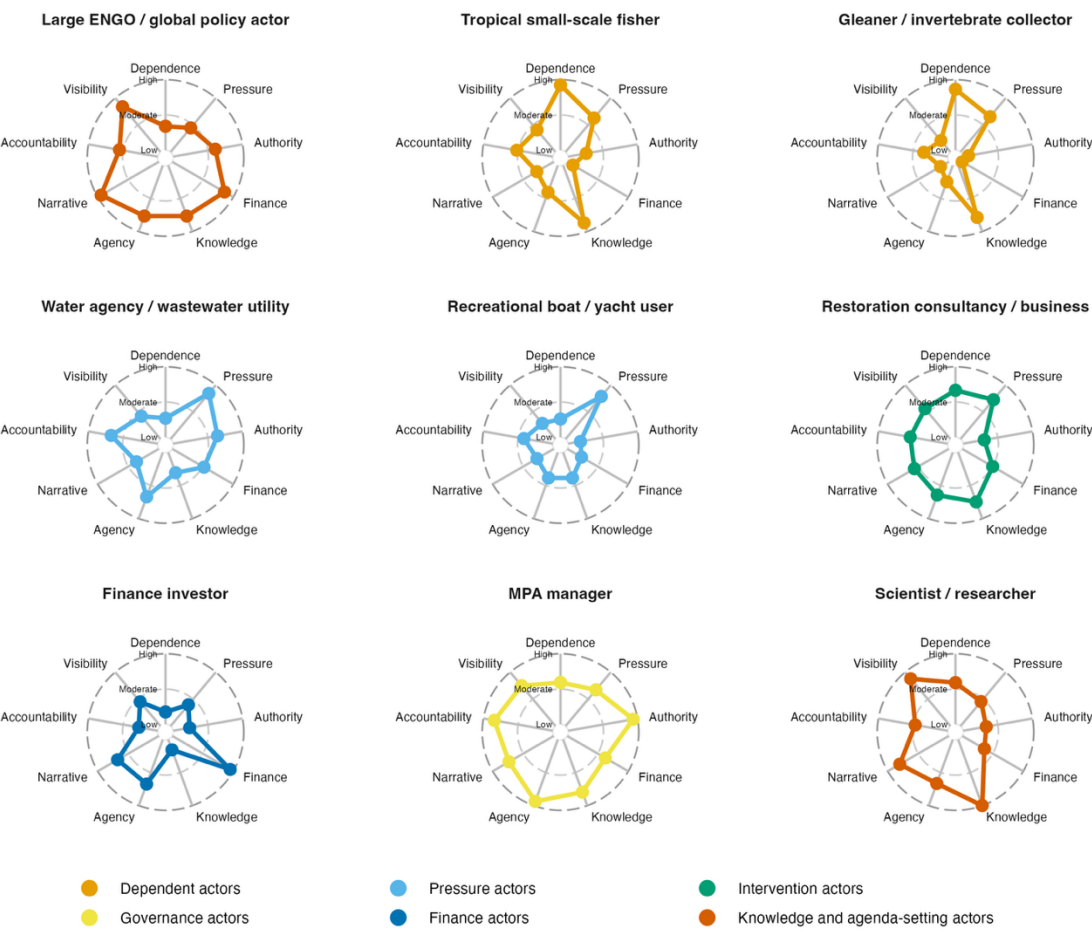


Figure 1. Expert-informed actor profiles reveal distinct social-ecological positions in seagrass conservation. Radar plots show selected actor profiles scored across nine diagnostic attributes: dependence, pressure or impact, governance authority, financial influence, knowledge contribution, capacity to alter outcomes, narrative influence, accountability and visibility. Scores were assigned on a three-point ordinal scale, where 0 = low or absent, 1 = moderate, indirect or context-dependent, and 2 = high, direct or central, and then averaged across experts. Selected profiles illustrate contrasts across dependent, pressure, intervention, governance, finance, and knowledge and agenda-setting actors. Point colours indicate actor family.

Mean scores on individual attributes showed clear differences among actor families (Figure S1). Dependent actors, including small-scale fishers and gleaners, scored highest for dependence (mean = 1.6) and knowledge contribution (1.6), but much lower for governance authority (0.4) and financial influence (0.2). Pressure actors scored highest for direct pressure or impact (1.6), reflecting their capacity to alter meadow condition through physical disturbance, infrastructure, extractive activity, nutrient inputs or sediment pathways. Governance actors scored highest for governance authority (1.7), capacity to alter outcomes (1.7) and accountability (1.6). Finance actors scored highest for financial influence (1.9) and

showed high narrative influence (1.4), but lower accountability (0.5). Knowledge and agenda-setting actors scored highest for knowledge contribution (1.5), narrative influence (1.4) and visibility (1.3).

Literature visibility and material leverage are misaligned

Material leverage (ability to alter seagrass outcomes based on combining scores for authority, capacity, financial influence, and direct pressure) scores varied strongly among actor profiles (Figure S2). Government agencies and management authorities had the highest material leverage score (1.8), followed by MPA managers (1.6), port and marina developers (1.5), fisheries managers (1.4), water agencies and wastewater utilities (1.3), and large Environmental Non-Governmental Organizations (ENGOS) or global policy actors (1.3). These profiles combine different forms of influence: formal authority, implementation capacity, financial influence or direct pressure on ecological processes.

Hidden leverage (ability to alter seagrass outcomes relative to literature visibility) was highest for fisheries managers (1.3), large ENGOS and global policy actors (1.3), restoration consultancies and businesses (1.0), philanthropic donors (1.0), and government agencies and management authorities (1.0; Figure 2). These actors had relatively high material leverage compared with their literature visibility. By contrast, some high-leverage actors were already highly visible in the literature (Figure S2), including MPA managers and port or marina developers. The mismatch therefore does not simply separate “visible” and “invisible” actors but identifies profiles whose capacity to alter and influence seagrass outcomes may exceed their explicit recognition in actor-relevant seagrass research. This suggests that some of the actors most important to ecological recovery sit partly outside the conventional seagrass conservation setting.^{11,37,40}

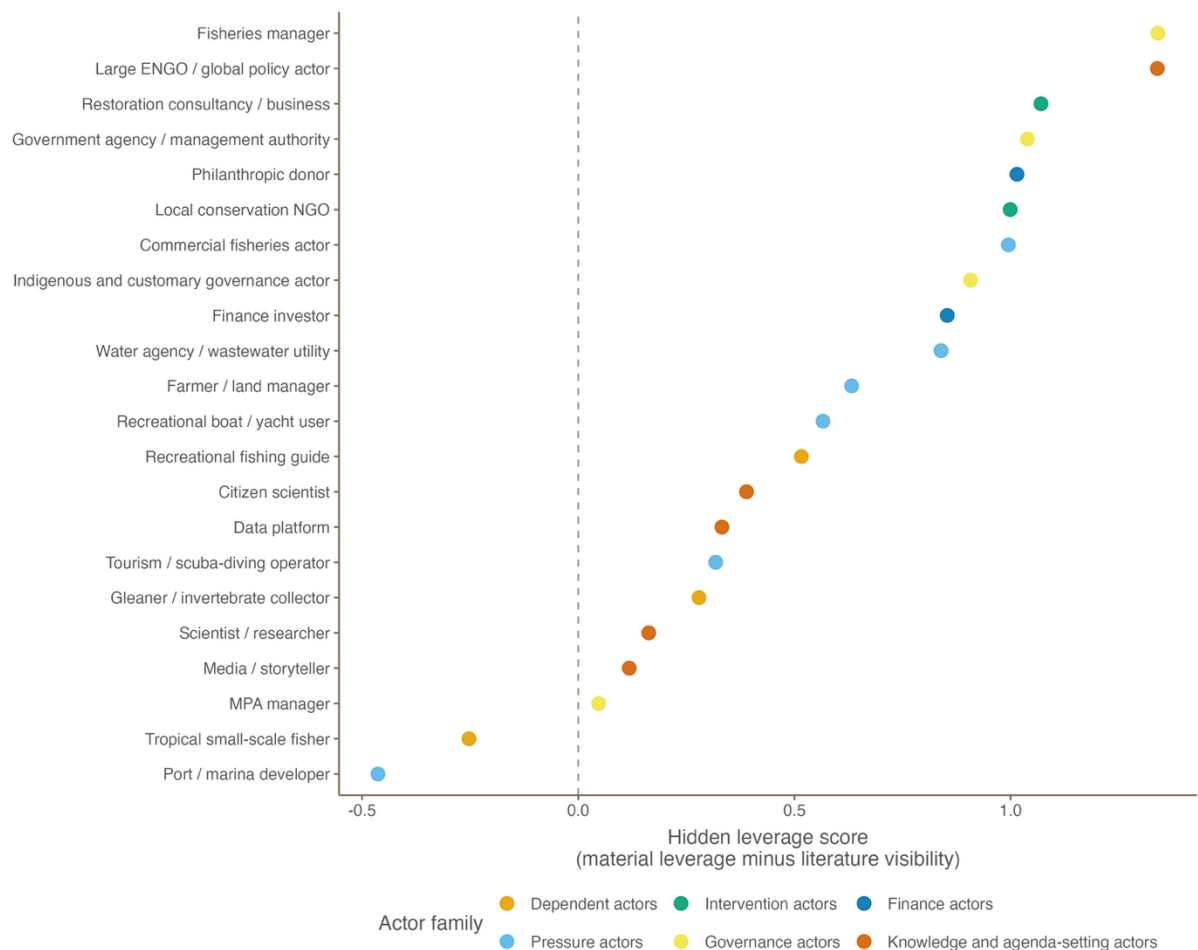


Figure 2. Hidden leverage identifies actor profiles whose capacity to shape seagrass outcomes exceeds their visibility in literature. Hidden leverage was calculated as material leverage minus rescaled literature visibility. Material leverage was estimated as the mean of four expert-scored attributes: pressure or impact, governance authority, financial influence and capacity to alter outcomes. Literature visibility was estimated as the number of actor-relevant records in which profile-specific terms appeared in titles or abstracts, then rescaled to the same 0 to 2 range as the expert-scored attributes. Positive values indicate actor profiles with greater potential leverage than explicit recognition in the literature, while negative values indicate profiles that are more visible relative to their material leverage.

Actor asymmetries shape seagrass conservation

The scoring exercise revealed four recurrent asymmetries (Figure 3). The first asymmetry was an authority-dependence gap. Dependence exceeded authority most strongly for gleaners and invertebrate collectors (-1.58), tropical small-scale fishers (-1.33), tourism and scuba-diving operators (-0.80), commercial fisheries actors (-0.77), and recreational fishing guides (-0.76). By contrast, authority exceeded dependence for port and marina developers (1.21), government agencies and management authorities (1.09), water agencies and wastewater utilities (0.74), and MPA managers (0.69). This pattern captures a central governance problem in that actors most directly connected to seagrass through food, livelihoods, place-based use

or coastal activity may have limited authority over the decisions that shape and sustain the future of the very meadows on which their own futures depend. Their exclusion is not only unjust but also removes critical traditional and local knowledge from conservation design.^{5,8,9,49}

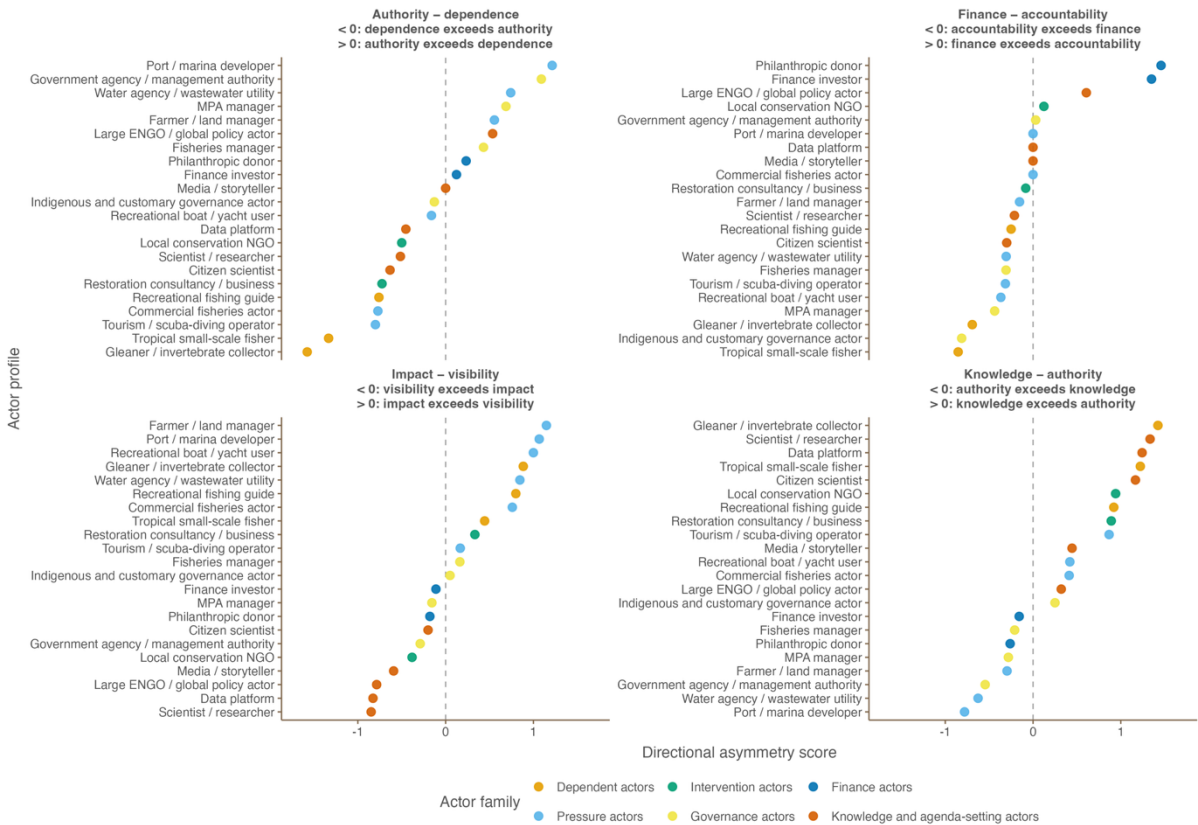


Figure 3. Directional asymmetries reveal mismatches between actor position and actor influence in seagrass conservation. Points show the difference between paired expert-scored attributes for each actor profile. Each panel title gives the paired attributes being compared. The dashed vertical line indicates approximate symmetry between attributes, whereas values further from zero indicate stronger asymmetry. Negative and positive values both indicate imbalance, but in opposite directions. For example, in the authority–dependence panel, negative values indicate that dependence exceeds authority, whereas positive values indicate that authority exceeds dependence. Colours indicate actor family. These scores are intended as diagnostic indicators of social-ecological mismatch rather than definitive measures of actor power.

The second asymmetry was an impact-visibility gap. Direct pressure or impact exceeded expert-scored visibility most strongly for farmers and land managers (1.15), port and marina developers (1.07), recreational boat and yacht users (1.00), gleaners and invertebrate collectors (0.88), and water agencies and wastewater utilities (0.85). These actors can influence meadow condition through nutrient and sediment flows (Berger et al., 2022), infrastructure, physical disturbance or extractive use, yet may not always be recognised as central seagrass conservation actors. Pressure reduction therefore depends on changing the

behaviours, duty, incentives or rules pertaining to actors who may sit outside conventional marine conservation institutions.⁴⁰

The third asymmetry was a finance-accountability gap. Financial influence exceeded accountability most strongly for philanthropic donors (1.46), finance investors (1.35), and large ENGOs or global policy actors (0.61). This does not mean these actors necessarily produce poor outcomes. However, it shows that actors able to shape funding priorities, investment pathways or public narratives may not be equally accountable for ecological persistence, local benefit, rights or long-term monitoring. Where accountability is weak, financial and narrative power can pull conservation towards visible, novel or marketable actions rather than those that are shown to support equitable, effective and durable social-ecological recovery.^{35,46,50}

A fourth knowledge-authority gap was strongest for gleaners and invertebrate collectors, scientists, data platforms, small-scale fishers and citizen scientists, reinforcing that knowledge contribution and decision authority are often held by different actors. These asymmetries may help explain why ecological knowledge of seagrass does not automatically translate into effective conservation actions and outcomes. In many cases, the limiting factor may be authority rather than information, incentives rather than awareness, institutional fit rather than ecological value, and accountability rather than ambition, much of which is centred around actor family power dynamics.

DISCUSSION

Mapping the actor system behind seagrass conservation

Our analysis shows that seagrass conservation is shaped by distinct actor groups whose different profiles influence whether conservation action is possible, legitimate and durable. We identify six broad actor families, show that their visibility in the seagrass literature is uneven, and demonstrate that material leverage, literature visibility and accountability do not always align. As conservation agendas converge on 2030, seagrass conservation is being asked to deliver across multiple overlapping goals, including area-based protection, ecological restoration, blue carbon, biodiversity recovery, monitoring and nature-positive finance. Yet the actors who determine whether these agendas become durable outcomes are often distributed across different sectors, jurisdictions and scales. This creates a central challenge for the next phase of seagrass conservation: ambitions may be global, but delivery depends on actor systems that are local, sectoral, politically fragmented and unevenly accountable.

This finding addresses a central gap in seagrass social-ecological science. Over the last two decades, seagrass science has developed a sophisticated ecological vocabulary. We now

describe decline trajectories, carbon stocks, anthropogenic pressures and restoration bottlenecks with increasing precision.^{24,25,27,51} Increasingly, social contexts and understandings are informing planning, capacities, and appropriate actions for seagrass conservation.^{36,38,52} However, we are still less able to describe the actor systems and dynamics that determine whether boating pressure is reduced, catchment nutrients are controlled, fishers participate in governance, restoration targets are realistic, carbon finance is equitable, or citizen science data influence decisions. This is the social-ecological gap our framework addresses. Seagrass meadows are shaped by biophysical, ecological, hydrodynamic and environmental processes, but like other governed coastal systems, they are also shaped by livelihoods, institutions, incentives, knowledge, finance and authority.^{13,53}

This actor-centred framing is consistent with wider social-ecological systems research, which has long challenged the separation of stewardship action and ecological condition from human agency, institutions and power. Work on common-pool resources, protected areas, small-scale fisheries and conservation planning shows that environmental outcomes emerge from interactions among resource systems, resource users, governance arrangements, knowledge, markets including their value chains and wider social settings.^{1,4,8,12} Seagrass conservation fits this logic closely. Problems that appear ecological are often also problems of authority, incentives, legitimacy, scale and institutional fit.

Moving beyond generic stakeholders

The language of “stakeholders”, widely used in seagrass science and conservation more broadly, does not fully reflect the complexity of actor systems and can obscure differences in power, dependence, influence, legitimacy and responsibility. A gleaner collecting food from an intertidal meadow, a water company managing wastewater infrastructure, and a media organisation amplifying restoration stories do not occupy the same position in the social-ecological system, and yet they are all relevant actors within seagrass conservation. Actor-centred analysis starts from these differences, asking how actors are connected to seagrass, what they can change, what motivates them, what knowledge they hold, what authority they exercise and who they are accountable to.^{8,32}

Short et al.⁸ showed that small-scale fisheries and aquaculture actors are not a homogeneous group. Their analysis demonstrates substantial diversity within actor types, including differences in technology, markets, governance, access, products, livelihood strategies and proximity to consumers. We extend this logic from a sectoral focus on small-scale aquatic food actors to a conservation focus on the wider actor landscape shaping seagrass social-ecological systems. Our findings show diversity among actor profiles, including actors who

depend on, pressure, restore, govern, finance, study and narrate seagrass, while also pointing to likely diversity within each profile. Small-scale fishers, tourism operators, water agencies, restoration practitioners, investors and conservation NGOs are themselves heterogeneous, and can vary in influence spatially. Treating these profiles as internally uniform would repeat the simplification that actor-profile approaches were designed to avoid. As such, the framework should be read as a first-order map of actor positions, not a substitute for place-based analysis of within-profile diversity.

Recognising hidden leverage

One of the clearest implications of our analysis is that some actors with substantial capacity to influence seagrass outcomes are not always the actors most visible in seagrass conservation research or practice. Conservation interventions are often organised around ecological need, then routed through actor systems marked by unequal authority, fragmented mandates, constrained funding, contested incentives and uneven knowledge. This creates a problem of governance and institutional fit as much as ecological design.⁵⁴ In seagrass, that mismatch appears repeatedly. Restoration may be technically plausible but institutionally fragile.³⁹ Protected areas may include seagrass while lacking authority over upstream sediment or nutrient inputs.^{27,37} Carbon projects may attract finance but fail to clearly identify community beneficiaries and future claimants,⁵⁰ and monitoring platforms may improve data access but fail to change management if no actor is responsible for a response.^{43,44} Seagrass conservation does not fail only because science is incomplete, but also because the actors with the power to influence governance, rules, management activities and outcomes are missing, misaligned or unaccountable.

This challenge is not unique to seagrass conservation. Protected areas underperform when boundaries are disconnected from enforcement, legitimacy, livelihoods or external pressures.^{4,5,12,55} Restoration effectiveness underperforms when technical delivery is prioritised over the social, institutional and ecological conditions that allow recovery.⁵⁶ Ecological monitoring loses force and yields limited governance impact when scientific evidence lacks institutional pathways for integration into authority and/or policy processes.⁵⁷ Finance can accelerate action, but can also redirect attention towards what is visible, fundable or marketable rather than what is durable, just or ecologically necessary.⁵⁸ Seagrass conservation is now entering this same terrain, and it should not have to relearn these lessons slowly.

Addressing actor asymmetries

The actor asymmetries identified here point to a practical problem for seagrass conservation: the actors most affected by decisions, the actors producing pressures, and the actors holding authority are often not the same. Area-based protection provides the clearest example. A meadow can sit inside a protected area and still decline if the relevant actors sit outside the protected-area mandate.^{27,59,60} Nutrient loading, sediment runoff, wastewater discharge, coastal infrastructure and boating pressure are often governed through separate institutions, jurisdictions and incentives.¹⁴ A protected area boundary can make seagrass visible while leaving the causes of decline untouched. Protection therefore only becomes meaningful when ecological pressure, regulatory authority, compliance capacity and social legitimacy align.

Regeneration raises a different but related challenge, with restoration not being applicable in all locations.⁶¹ The expanding restoration agenda has brought energy, funding, public awareness and media attention to seagrass conservation, but it has also increased the risk that planting becomes a visible proxy for ecological recovery. Recovery depends on site condition, ecological bottlenecks, permits, monitoring, funding cycles, local legitimacy and long-term stewardship, not only on seeds, shoots or planting methods.^{39,47,52,62} The actor system around restoration determines whether intervention becomes ecological recovery, public engagement, donor performance, technical experimentation or reputational storytelling.

Some of the most consequential actors for seagrass recovery may be the least likely to identify as seagrass actors. Water agencies, wastewater utilities, farmers, catchment managers, planners and regulators shape the nutrient, sediment, turbidity and land-use conditions under which meadows persist or recover. This unnoticed relevance may be particularly relevant for actors whose influence is highly spatially variable, such as farmers or planners in different watersheds with and without seagrass downstream. If these pressures remain unresolved, marine conservation works downstream of failure. In this sense, land-sea governance is not peripheral to seagrass conservation, it is one of its core delivery systems.^{11,16,63}

The same actor lens is also needed across seagrass-linked fisheries, food systems, tourism and recreation. Seagrass is often treated as fish habitat, but seagrass-associated fisheries are also livelihood systems, food systems, knowledge systems and governance systems. They connect small-scale fishers, gleaners, recreational guides, commercial fisheries actors, managers, buyers and consumers. Embedding seagrass in ecosystem-based fisheries management therefore requires more than recognition of nursery function. It requires attention to food security, recreational economies, local knowledge, market connections and habitat-dependent production, alongside their spatial coupling and spillover effects. Tourism and recreation are similarly mixed pathways. They can support conservation finance, stewardship

and local livelihoods, while also intensifying pressure through infrastructure, boating, trampling and coastal development.³⁸

Together with recent participatory mapping approaches,⁴² our results reinforce the idea that seagrass knowledge systems are co-produced across heterogeneous actor networks, yet remain structurally decoupled from governance authority. Knowledge and monitoring are only powerful when they travel into decision-making systems. Citizen science, Indigenous and local ecological knowledge, monitoring platforms, and academic research collectively increase the visibility of seagrass systems, but this increased visibility does not automatically translate into conservation impact. Evidence must reach actors with authority, contributors must see feedback and action, and monitoring must be linked to a response and adaptation where necessary. Otherwise, monitoring can document decline while leaving the actor system unchanged.^{15,64,65}

Public narratives constitute an additional layer through which seagrass systems are shaped and interpreted. Media actors, funders, large NGOs, scientists, and restoration practitioners influence how seagrass conservation is framed, prioritised, and communicated to the public and decision-makers.²⁹ Restoration-centred narratives can mobilise hope and support, but they can also narrow the agenda if they crowd out protection, pressure reduction, monitoring, rights and governance.^{66,67}

Implications for seagrass conservation pathways

Our findings have several implications for research, policy and practice within a seagrass social-ecological systems agenda. Seagrass conservation planning increasingly accounts for social factors alongside ecological conditions,^{36,52} but actor mapping is vital to interpret, contextualise, and act on these patterns. Site condition, threats and restoration potential remain essential, but they are incomplete without identifying who depends on seagrass, who produces pressure, who holds authority, who controls finance, who generates knowledge and who is accountable for outcomes.^{5,8,12} Actor diversity should be treated as a source of adaptive capacity rather than only a complication. Diverse actors bring diverse knowledge, resources, legitimacy, authority and capacity. Conservation that recognises this diversity can identify a wider set of realistic leverage points, anticipate trade-offs and design interventions that are more likely to persist.^{6,49}

Future research directions

Future work should move from broad actor profiles towards empirical mapping of actor systems in specific seagrass spaces. The ideas developed here provides a first-order

structure, but actor positions will vary across governance systems, tenure arrangements, markets, histories and ecological settings. Participatory actor mapping, social network analysis, institutional analysis, political economy approaches and comparative case studies could test where actor visibility, authority, accountability and ecological influence align or diverge. This would be particularly valuable in locations where seagrass recovery depends on actors outside conventional marine conservation. Future work should also examine how actor profiles change over time, especially as blue carbon, restoration finance, nature markets, citizen science platforms and global conservation targets reshape who has influence over seagrass futures.

Conclusions

Seagrass conservation is at an important juncture, with both protection and restoration essential to achieve and sustain global recovery.⁶⁸ Seagrass meadows are being mapped, valued, restored, financed and narrated at increasing speed and frequency. However, without a stronger social-ecological grounding, this momentum risks reproducing familiar weaknesses. As mapping the social components of seagrass systems gains traction, we cannot afford to overlook the actor dynamics at play. The central challenge is the organisation of human action around ecological systems. The future trajectory of seagrass will be shaped by actors whose dependence, authority, finance, knowledge, visibility and accountability rarely align.

Some actors live with seagrass daily yet remain marginal in decision-making. Others damage seagrass without recognising their role. Some govern from institutions that do not match ecological processes; others finance and narrate conservation from a distance. Seagrass conservation therefore needs stronger social-ecological science because conserving seagrass is, in practice, a problem of governing relationships between people and ecosystems; upstream and downstream actors; finance and accountability; knowledge and action; and ecological recovery and social legitimacy. Moving beyond meadow-centred conservation does not weaken ecological science but gives it the actor-aware social framework it needs to change outcomes and secure the future of seagrass systems.

METHODS

Study design

We developed a heuristic actor-centred framework to examine actor diversity within seagrass social-ecological systems. The analysis combined five steps: a structured scan of actor-relevant seagrass literature, conservative title-and-abstract coding, synthesis of recurring

actor families and conservation pathways, expert scoring of actor profiles, and quantitative processing of actor visibility, material leverage and actor asymmetry metrics.

The literature scan was designed as a structured mapping exercise rather than a systematic review or meta-analysis. We used an approach aligned with scoping and evidence-mapping methods, which use broad searches and title-and-abstract coding to characterise the structure of a literature, identify clusters and gaps, and support conceptual synthesis rather than estimate pooled effects.⁶⁹⁻⁷² Our aim was to build a conceptual framework for identifying actor diversity, hidden leverage points and social-ecological asymmetries within seagrass conservation.

Literature scan

We conducted a broad Web of Science search to identify seagrass research with potential actor relevance. The search combined seagrass terms with actor-oriented terms relating to stakeholders, fishers, gleaners, resource users, households, livelihoods, Indigenous and local knowledge, managers, institutions, policy, tourism, recreation, boating, farming, finance, NGOs, citizen science, volunteers and media (Supplementary Material). The search was intentionally broad so that actor-relevant studies would not be missed simply because they did not use the term “stakeholder”.

The search returned 2,839 records with abstracts. For each record, we retained bibliographic metadata, title, abstract, publication year, source and DOI where available. Titles and abstracts were used as the primary basis for screening and coding. Full texts were not reviewed systematically because the purpose of the scan was to map the visibility of actors and conservation pathways in the seagrass literature, rather than to extract detailed findings from each study.

Title-and-abstract screening

Records were screened using a three-level actor-relevance classification. A record was coded as “Yes” when people, institutions, users, managers, communities, governance, policy, livelihoods, participation, finance, tourism, citizen science or other social actors were clearly central to the study. A record was coded as “Partial” when actors or social dimensions were mentioned in the title or abstract, but were secondary, incidental or ambiguous. A record was coded as “No” when the study was primarily ecological, biophysical, technical or methodological, with no clear actor relevance in the title or abstract.

Screening was deliberately conservative. Records were not treated as actor-relevant simply because they included broad terms such as conservation, restoration, management, carbon, monitoring or ecosystem services. Instead, actor relevance had to be visible in the title or abstract through a clear focus on people, institutions, users, decision-making, participation, governance, knowledge, finance, livelihoods or other social dimensions. Where relevance was uncertain, records were coded as Partial rather than forced into the strict actor-relevant dataset.

Of the 2,839 screened records, 1,129 were classified as actor-relevant, 1,067 as partial and 643 as not actor-relevant. The main actor-visibility analysis used only the 1,129 strict actor-relevant records. This reduced the risk of inflating actor visibility through papers where actors were mentioned only incidentally. Partial records were retained in the coded dataset but were not used in the primary visibility analysis.

Actor-theme and conservation-pathway coding

Each record was coded for the primary actor theme and primary conservation pathway using the title and abstract. Coding was guided by predefined categories, but final assignments were made conservatively through title-and-abstract interpretation.

Actor-theme categories corresponded to six actor families: dependent actors, pressure actors, intervention actors, governance actors, finance actors, and knowledge and agenda-setting actors (see Table 1). Dependent actors were actors whose food, income, culture, recreation, identity or wellbeing was directly linked to seagrass or seagrass-associated species. Pressure actors were actors whose activities directly or indirectly degraded seagrass condition or altered the ecological processes that sustain meadows. Intervention actors were actors deliberately seeking to alter seagrass trajectories through conservation, restoration, advocacy, stewardship or applied action. Governance actors were actors shaping rules, access, enforcement, permits, planning, tenure, policy or management authority. Finance actors were actors shaping conservation through funding, investment, crediting, corporate claims or financial incentives. Knowledge and agenda-setting actors were actors shaping what is known, measured, valued, communicated or prioritised.

Conservation-pathway categories described the main social-ecological process associated with each record. These pathways were fisheries and food systems, governance and policy, knowledge and monitoring, tourism and recreation, restoration and recovery, protection and marine protected areas, water quality and catchment management, coastal development and spatial planning, blue carbon and finance, and rights and equity.

Records were assigned a primary actor theme and primary conservation pathway only where the title and abstract provided sufficient evidence for a clear classification. Where multiple actor themes or pathways were equally plausible, the record was coded as ambiguous rather than forced into a single category. This approach reduced false precision in studies that spanned several actor groups or conservation pathways. The coded dataset retained classification notes and ambiguous records as an audit trail.

Actor-family and actor-profile development

For the purpose of actor-profile development, actor-families were treated as analytical categories rather than fixed identities because actors may occupy multiple positions at once. For example, a fisher may also be a citizen scientist, restoration volunteer or customary governance actor, a conservation NGO may produce knowledge, implement restoration, mobilise finance and influence policy and a government agency may regulate, fund, monitor and narrate conservation.

Within the six families, 22 recurring actor profiles were identified for expert scoring: tropical small-scale fisher; gleaner/invertebrate collector; recreational fisher/guide; recreational boat/yacht user; tourism/scuba-diving operator; port/marina developer; farmer/land manager; water agency/wastewater utility; commercial fisheries actor; local conservation NGO; restoration consultancy/business; MPA manager; government agency/management authority; fisheries manager; Indigenous and customary governance actor; philanthropic donor; finance investor; scientist/researcher; citizen scientist; data platform; media/storyteller; and large ENGO/global policy actor.

The actor families and profiles were designed to reveal system position rather than to provide an exhaustive census of all seagrass actors. Rather, they capture distinct ways in which people and institutions depend on seagrass, affect seagrass condition, govern access and rules, finance action, implement interventions, produce knowledge or shape public and policy narratives.

Expert scoring exercise

Next, we developed an expert scoring exercise to compare actor profiles across nine diagnostic social-ecological attributes: dependence, pressure or impact, governance authority, financial influence, knowledge contribution, capacity to alter outcomes, narrative influence, accountability and visibility. The exercise was designed to support conceptual analysis rather than produce a definitive global measurement of actor power.

Experts were identified by the lead author based on their contributions to seagrass science, marine social-ecological research, conservation practice, restoration, policy or management, and their leadership or participation in national and international seagrass initiatives. Fifty experts were invited to participate. Thirty-five completed the scoring exercise. In both cases, the expert pool included the lead author. Experts were asked to score only the actor profiles for which they had relevant knowledge through research, conservation, restoration, policy, management or practice. Each actor profile was scored across the nine attributes using a three-point ordinal scale: 0 = low, absent or generally not part of the actor's role; 1 = moderate, indirect, variable or context-dependent; and 2 = high, direct or central to the actor's role. Contributors were provided with definitions of each attribute and descriptions of each actor profile.

Scores were intended to reflect the typical or general role of each actor profile in seagrass conservation, while recognising that actor roles vary across contexts. Blank scores were treated as missing values rather than zeros. For each actor-profile attribute, we calculated the mean score across available expert responses. We also retained the number of expert scores contributing to each actor-profile attribute and calculated summary measures of variation.

Actor-profile literature visibility

For each of the 22 actor profiles, we then estimated literature visibility using the strict actor-relevant database. Visibility was calculated as the number of strict actor-relevant records in which profile-specific terms appeared in the title or abstract. This approach follows the logic of bibliometric and evidence-mapping methods, where title, abstract and keyword terms are used to characterise explicit visibility, thematic structure and gaps within a research field.^{72,73}

Profile-specific terms were developed for each actor profile and included common synonyms and related terms (Supplementary Table). For example, visibility terms for recreational boat and yacht users included "boat", "boating", "boater", "yacht", "anchoring", "anchor", "mooring" and "sailing". Terms for finance investors included "blue carbon", "carbon credit", "carbon market", "carbon finance", "investor", "investment", "offset", "corporate", "private sector", "CSR" and "ESG".

For each actor profile, literature visibility was calculated as the number of strict actor-relevant records in which at least one profile-specific term appeared in the title or abstract. A single record could contribute to the literature visibility score of more than one actor profile if it contained terms associated with multiple profiles. Literature visibility should therefore be

interpreted as an index of explicit recognition in the seagrass actor literature, rather than a complete measure of actor importance, power or ecological impact. Some actors may be discussed in full texts without appearing in titles or abstracts. Conversely, some search terms may capture broad actor groups that vary substantially across contexts.

Material leverage and actor asymmetries

Because different actors influence seagrass in different ways, we estimated material leverage as a heuristic measure of each actor profile's plausible capacity to alter seagrass outcomes. Drawing on leverage-point thinking in sustainability science, this emphasises that change in complex social-ecological systems may depend not only on direct pressures, but also on governance, incentives, institutions, information flows and the capacity to act.⁷⁴⁻⁷⁶ Material leverage was calculated as the mean of four diagnostic attributes: pressure or impact, governance authority, financial influence and capacity to alter outcomes. These attributes were selected because they represent major ways actors can shape ecological trajectories, institutional decisions, resource allocation or conservation action. Material leverage was calculated as:

$$\text{Material leverage} = \frac{(\text{pressure} + \text{authority} + \text{finance} + \text{agency})}{4}$$

We then compared material leverage with literature visibility to identify actor profiles whose potential capacity to shape seagrass outcomes may be greater than their explicit recognition in seagrass research. Before calculating hidden leverage, literature visibility counts were rescaled to the same 0–2 range as the expert-scored attributes. Hidden leverage was then calculated as:

$$\text{Hidden leverage} = \text{material leverage} - \text{literature visibility}$$

Importantly, this comparison was used more as a diagnostic tool, rather than a quantitative estimate of actor power. We also calculated four actor asymmetry scores to identify mismatches between different forms of social-ecological position. Authority-dependence asymmetry compared governance authority with dependence. Impact-visibility asymmetry compared pressure or impact with expert-scored visibility. Finance-accountability asymmetry compared financial influence with accountability. Knowledge-authority asymmetry compared knowledge contribution with governance authority. Each asymmetry was calculated as a simple difference between paired attribute scores, for example, authority-dependence asymmetry = governance authority – dependence. Positive and negative values indicate the

direction of imbalance. These scores were used to support interpretation of recurrent actor asymmetries, not to make inferential statistical claims.

Limitations

This framework is heuristic and interpretive. It is intended to clarify actor diversity and generate analytical insight, not to replace place-based stakeholder analysis or mapping. Actor positions vary across geographies, governance systems, political economies, tenure arrangements and ecological settings. The same actor type may hold high authority in one context and little authority in another. Literature visibility also does not necessarily correspond to policy influence, lived importance or local legitimacy.

The title-and-abstract coding approach improves consistency and transparency, but it depends on the quality of the search terms, category definitions and abstract wording. Some relevant actor relationships may not be visible in abstracts, while some terms may be too broad and capture multiple meanings. To reduce this risk, ambiguous records were coded conservatively, strict relevance was used for the main visibility analysis, and the full coding logic, actor terms and pathway terms are provided in the supplementary material.

The expert scoring approach also involves judgement. To improve transparency, we define each attribute, describe the scoring logic and provide the scoring exercise, actor-profile definitions and scoring outputs in the supplementary materials. Future applications could refine the framework through participatory scoring, Delphi methods, empirical stakeholder mapping, social network analysis or case-study comparison. The framework should therefore be understood as a first-order map of actor positions within seagrass social-ecological systems and therefore useful for structuring analysis, identifying hidden leverage points and guiding more context-specific conservation, research and practice.

Resource availability

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Data and code availability

The minimum dataset generated during and/or analysed during the current study is available from the corresponding author on reasonable request.

Supplementary Material

Document S1. Figures S1 and S2, and Supplemental Methods 1.

Author contributions

B.L.H.J. led the study, developed the conceptual framing, designed the analysis, analysed the data, prepared figures and drafted the manuscript. S.O.B., S.W.J.C., L.C., M.D.L.T.-C., G.D.G., N.M.H., J.R.K., K.M.M., A.F.M., I.O., R.S., L.S.S., O.R.T. and M.W. contributed expert scoring, interpretation and manuscript text or revisions. N.J.B. contributed to latter conceptual grounding and manuscript revision. J.S.B. contributed to manuscript revision. N.A.-M., V.M.A., N.A., R.E.B., L.B., J.M.S.C., A.J.C., H.S.D., A.A.D., C.G., R.J.L., L.J.M., L.M.N., J.L.S.O., J.S.R., A.I.S., F.T., S.U., B.V., S.V. and S.W.-H. contributed expert scoring.

Declaration of interests

The authors declare no competing interests.

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Actor family	System position	Illustrative actor profiles	Justification
Dependent actors	Actors whose food, income, culture, recreation, identity or wellbeing is directly linked to seagrass or seagrass-associated resources.	Small-scale fishers; gleaners and invertebrate collectors; recreational fishers and guides; commercial fisheries actors.	Small-scale fishers and gleaners use seagrass-associated fish and invertebrates for food, income and household wellbeing, while also holding local ecological knowledge of habitat change, species, seasons and fishing grounds. Commercial and recreational fisheries may also benefit from seagrass nursery and habitat functions.
Pressure actors	Actors whose activities directly or indirectly damage seagrass meadows or alter the ecological processes that sustain them.	Recreational boat and yacht users; tourism and scuba-diving operators; port and marina developers; farmers and land managers; water agencies and wastewater utilities; commercial fisheries actors.	Pressure pathways include anchoring, propellor and mooring damage, coastal infrastructure, dredging, land reclamation, tourism pressure, nutrient loading, wastewater discharge, sediment runoff and catchment land use. These actors often influence meadow condition from beyond the spatial boundaries of seagrass management
Intervention actors	Actors deliberately seeking to change seagrass trajectories through conservation, restoration, advocacy, stewardship or applied action.	Local conservation NGOs; restoration consultancies and businesses; ecological contractors; community groups; restoration volunteers.	Intervention actors shape restoration practice, public expectations, monitoring, stewardship and conservation delivery. Their work is influenced by site condition, ecological bottlenecks, long-term maintenance, community co-production, funding cycles and incentives for visible outputs
Governance actors	Actors shaping rules, access, enforcement,	MPA managers; government agencies and management	Seagrass governance often crosses fragmented mandates for biodiversity, water quality, fisheries, agriculture,

	permits, planning, tenure, policy and management authority.	authorities; fisheries managers; permitting bodies; Indigenous and customary governance actors.	planning and infrastructure. Protected areas may include seagrass but lack authority over land-based pressures, while Indigenous and customary governance actors may hold rights, legitimacy and place-based authority that formal systems do not
Finance actors	Actors influencing conservation through funding, investment, crediting, corporate claims or financial incentives.	Philanthropic donors; finance investors; corporate funders; blue carbon investors; biodiversity-credit actors; development finance institutions.	Finance actors shape what is possible, attractive and reportable. Blue carbon and nature-finance pathways can mobilise resources, but also create risks around tenure, benefit-sharing, accountability, carbon claims, project timelines and incentives for marketable restoration narratives
Knowledge and agenda-setting actors	Actors shaping what is known, measured, valued, communicated or prioritised.	Scientists and researchers; citizen scientists; Indigenous and local knowledge holders; data platforms; media and storytellers; large ENGOs and global policy actors.	Knowledge actors make seagrass visible through research, monitoring, citizen science, local knowledge, data platforms and public narratives. These pathways can support conservation, but their value depends on whether evidence reaches decision-makers, contributors receive feedback and narratives do not narrow conservation to only the most visible interventions

Table 2. Diagnostic attributes used to compare seagrass actor profiles. The table defines the nine social-ecological attributes used in the expert-informed scoring exercise: dependence, pressure or impact, governance authority, financial influence, knowledge contribution, capacity to alter outcomes, narrative influence, accountability and visibility. Each actor profile was scored for each attribute using a three-point ordinal scale, where 0 = low or absent, 1 = moderate, indirect or context-dependent, and 2 = high, direct or central. The attributes were designed to compare actor position within seagrass conservation, not to provide a universal measure of actor power or importance.

Attribute	Guiding question	Description
Dependence	How strongly is this actor's wellbeing, income, identity, culture, recreation or mandate tied to seagrass?	Captures whether the actor relies on seagrass or seagrass-associated species for food, livelihoods, cultural practice, recreation, identity, business activity or institutional purpose.

Pressure / impact	Does this actor directly or indirectly alter seagrass condition or associated ecological processes?	Captures whether the actor can damage, degrade, restore, disturb or otherwise alter seagrass through physical disturbance, pollution, resource extraction, infrastructure, restoration or other actions.
Authority	Can this actor make, enforce or shape rules, permits, access, planning or management decisions?	Captures formal, customary, institutional or informal authority over coastal access, resource use, enforcement, permits, planning, restoration approvals or conservation decisions.
Finance	Can this actor direct funding, investment, market incentives or project priorities?	Captures the actor's ability to provide, withhold or direct financial resources, shape investment decisions, create market incentives, or influence project design through funding.
Knowledge	Does this actor hold or produce knowledge relevant to seagrass conservation?	Includes scientific knowledge, local knowledge, Indigenous knowledge, practitioner knowledge, regulatory knowledge, monitoring data, observational knowledge or historical baselines.
Agency	Can this actor realistically alter social or ecological outcomes?	Captures practical capacity to change behaviour, rules, funding, pressure, intervention design, public support or ecological condition. This is broader than formal authority.
Narrative	Can this actor shape public, donor, media or policy attention?	Captures ability to influence how seagrass conservation is framed, communicated, funded, prioritised or understood by wider audiences.
Accountability	Is this actor answerable for ecological persistence, social outcomes, harm or benefit-sharing?	Captures whether the actor is formally, politically, socially, legally or morally accountable for seagrass outcomes, community impacts, conservation success or damage caused.
Visibility	Is this actor recognised in seagrass science, policy or conservation practice?	Captures whether this actor is commonly visible in seagrass research, conservation planning, management

		discussions, funding proposals or policy frameworks.
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