Recognising patterns of vulnerability in a seagrass-dependent social-ecological system to support place-based management

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Abstract

Seagrass social-ecological systems are increasingly demonstrated to contribute to the well-being, livelihood opportunities and local economies of millions of people across coastlines globally. Seagrasses are also recognised for supporting endangered, culturally significant biodiversity and fisheries species. In the Palk Bay, Tamil Nadu region of southern India, we use a vulnerability framework to explore household and village scale sensitivity, exposure and adaptive capacity to social-ecological shocks. Through village consultations and household and key informant interviews with seagrass-dependent fishers, we reveal household- and village- scale vulnerabilities which can be grouped to present potential pathways towards social-ecological resilience. We found that fishing was the primary livelihood of most surveyed households and limited other livelihood options were reported. Households where fishing was the primary livelihood were found to be more sensitive to change than households with alternate primary livelihoods. At a village scale, exposure, sensitivity and adaptive capacity varied independently. Trends in adaptive capacity and exposure were used to inform categorisation of villages into a four-part management complex: priority support sites, co-management opportunity sites, preventative support sites, and stewardship or learning sites. In doing so, this work provides tailored approaches to bottom-up, place-based management in a data-poor small-scale fishery system.

Key words: Small-scale fisheries; Coastal livelihoods; Environmental governance; Livelihood diversification; Community-based conservation; Adaptive capacity.

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Introduction

Seagrass meadows are coastal social-ecological systems (SES) where vulnerability arises from the intertwining of human dependence on ecosystem goods and services, and the various and cumulative threats placed upon them (Cullen-Unsworth et al. 2014; Unsworth et al. 2014). For coastal communities, seagrass meadows provide essential ecosystem services for those that rely on nature for food security and household income (Jones et al. 2022). In seagrass proximate societies (Jones 2026), the daily lives and livelihoods of millions of people are directly linked to nearshore marine resources, and are, therefore, intricately connected to seagrass ecosystems (Jones et al. 2026).

Seagrass functioning, productivity and longevity are sensitive to numerous local and global scale stressors, including nutrient runoff, sedimentation, ocean warming and direct disturbance (Dunic et al. 2021; Turschwell et al. 2021; Jones et al. 2025). The cumulative impacts of these stressors drive the ongoing decline of seagrass ecosystems across the globe (Grech et al. 2018; Griffiths et al. 2020; Dunic et al. 2021; Turschwell et al. 2021). Such ecological declines are reported to disproportionately affect communities reliant on marine and fisheries resources with limited alternative livelihood options, where poverty limits the financial, technical and institutional resources that are needed to adapt to change (Quiros et al. 2018; Jones et al. 2022; Jones et al. 2026). In such contexts, reduced capacity to adapt to social, political or environmental changes reinforces the dependence of coastal peoples on marine and fisheries resources which can further increase their sensitivity to the environmental stressors acting upon seagrass ecosystems (Cinner et al. 2013; Jones et al. 2022). Vulnerability is, therefore, not simply determined by biophysical stressors, but emerges from the complex interactions between ecological conditions, governance and institutional arrangements, socio-political contexts, resource access and rights, individual capacity to adapt to change (Bennett et al. 2015; Thomas et al. 2019; Jones et al. 2022; Nair et al. 2026).

In the context of social and environmental change, vulnerability is defined as *the state of susceptibility to harm from perturbations* (Adger 2006). However, vulnerability is complex, not uniform across coastal systems, and is shaped by location specific social, economic, political, cultural, and environmental conditions (Adger 2006; Birkmann 2006; Folke 2007). Stressors that drive vulnerability in coastal communities are repeatedly reported as diverse and variable (Bennett et al. 2015). Conceptual frameworks are widely used to assess vulnerability to stressors, shocks, harm, hazards, or change (the impacts of climate change) in coastal SES. The components of vulnerability in these frameworks are typically described as 1) exposure to a stressor, 2) sensitivity to the stressor, 3) the capacity to adapt to the stressor (Cinner et al. 2013).

From vulnerability, pathways to resilience can emerge by addressing the relationships between ecological, social and political domains that reinforce or perpetuate vulnerability cycles (within seagrass systems) (Nair et al. 2026). As conceptualisations of

vulnerability shift from a focus on static conditions toward dynamic feedback processes, interventions that interrupt vulnerability can enhance system viability. Resilience-oriented outcomes can therefore emerge as the underlying drivers of vulnerability are addressed (Nair et al. 2026). Despite growing recognition of the importance of social dimensions of marine and coastal management for the long-term sustainability and legitimacy of management outcomes, social impacts are frequently underrepresented in coastal planning and decision making (Grimmel et al. 2019). Principles of place-based coastal management can align with the promotion of resilience outcomes (in seagrass SES), particularly where governance is tailored to reflect the complexity of local ecological conditions, cultural values and community knowledge, and broader political contexts (Koehn et al. 2013; Bennett et al. 2021). Biocultural approaches to management also recognise the interconnectedness of biological and cultural diversity, acknowledge the importance of cultural values, knowledge systems, and equitable participation in environmental stewardship, and realise that system resilience can be compromised by the collapse of any of these dimensions (Bridgewater and Rotherham 2019; Brondízio et al. 2021; Reyes-García et al. 2022). The expression of societal priorities through the surrounding social, cultural, political and economic systems shape ecosystem-based management approaches that may be suitable for localised conservation action (Loomis and Paterson 2014).

Engaging with the experiences, needs, values, and vulnerabilities of individuals, groups and communities connected to coastal ecosystems and resources provides insights for marine resource management. Such information can also contribute to the identification of social inequalities, power imbalances, unmet needs, and disparities in how benefits and disadvantages of coastal change and management are distributed across society (Bennett 2022). Integrating social and ecological data can support equity and justice in marine management and governance, yet methods for collecting and integrating social data are far less developed than those for marine biophysical data. Frameworks that explicitly integrate social and ecological dimensions are increasingly being developed to better represent the complexity of coastal social-ecological systems (Berkes 2017). These approaches can also support the development of more equitable and inclusive policies, management plans and governance arrangements by making social inequities and differential vulnerability more visible (Bennett et al. 2021; Singh et al. 2023).

Place-based co-management that promotes community participation, integrates local knowledge and scientific monitoring, supports community-led stewardship, and simultaneously addresses both ecological and social drivers of vulnerability can build trust among actors, level long-term power imbalances, voice unheard perspectives, and motivative action to enhance adaptive capacity, reduce exposure and sensitivity, and strengthen ecological recovery potential (Olsson et al. 2004; Berkes 2009; Nair et al. 2026). By embracing place-based management principles, local governance can be co-produced through the knowledge, values and priorities of local communities and create

opportunities to strengthen long-term social and ecological resilience (Olsson et al. 2004; Plummer and Armitage 2007; Armitage et al. 2009).

To date, few studies have examined how seagrass dependence shapes potential social vulnerability at household and village scales and how this can inform pathways to build social-ecological resilience. Using a case study from the Tamil Nadu region of Palk Bay, we quantified social vulnerability across households and villages engaged in seagrass-fisheries to provide insights for place-based management to support seagrass condition and social resilience.

Methods

Study region and scope

The study region was located along the Tamil Nadu coastline of Palk Bay, across the districts of Thanjavur and Pudukkottai. In 2022, this coastal zone was designated as a Dugong Conservation Reserve (DCR) to protect dugong and seagrass meadows. Participants in the study were located in villages adjacent to the DCR, who are dependent on seagrass ecosystems for their daily small-scale fishing activities, and typically use boats of a maximum 33 feet in length with an outboard engine.

Study design

Data collection was conducted through a multi-method approach. Social indicators for vulnerability were derived from a combination of interviews with household key informants, village consultations, and observational transects conducted within villages in the Palk Bay study region.

Data collection

Household interviews

A purposive sampling strategy was adopted to recruit individuals for household interviews. Participants were recruited through a snowballing approach where individuals were recommended by village elders and other village members due to their involved in seagrass ecosystem resource use. Key informant interviews were also conducted with experienced fishers and community members to obtain greater depth of information on resource use and local ecological knowledge. A long-standing relationship between village elders and OMCAR exists, and it was through these relationships and the resulting network that participants were recruited. Interactions with participants were conducted in an ethically appropriate manner where prior to engagement of any participants with data collection processes, free prior informed consent for them to take part in the study was gained. Data collection was not conducted if consent was not granted.

Interviews were conducted using a semi-structured questionnaire comprised of closed- and open-ended questions. The questionnaire was structured around topics of household demographics, livelihoods and income, fishing practices, interactions with nearshore ecosystems, assets and infrastructure, health and social conditions, finance status, and government schemes.

Interviews were conducted verbally in Tamil, the native language spoken by the respondents. Using a questionnaire and written field notes to structure and record responses, each interview lasted between 4 and 5 minutes. Individual interviews were conducted with a total of 275 individuals, representing 275 households in 13 villages in the Tamil Nadu region of Palk Bay coastline. All interviews were undertaken between August 2024 and February 2025.

Participatory Resource Appraisal

Designed to generate community level insights into spatial resource use, Participatory Resource Appraisal (PRA) methods were used to record coastal and village features (Chambers 1994). Data were systematically collected in written field notes made during village consultations and observations of villages along driven transects. Villages in the PRA were selected as they were located within the 55 km stretch of coastline adjacent to the DCR. In each village a transect was driven by car perpendicular to the coast, along the coastal road. During this, presence/absence of village features were observed and recorded. Further discussions of village features and facilities were undertaken in consultations and key informant interviews with village members, with discussions held in public places (e.g., a village hall).

Data analysis

Spatial data and population proximity

Spatial data were used to complement the household interviews and village-level observations, and to situate each village within its wider coastal and population context. Village coordinates were generated for each surveyed village and used to create a spatial point layer in R.

To capture wider population pressure around each village, we calculated a Population Proximity Index using the *MarinePPI* package for R (Heery et al. 2026). MarinePPI estimates the density of nearby human populations around coastal or marine sites using gridded population data and buffer distances (Heery et al. 2026). We calculated MarinePPI values at 1, 2, 5, 10 and 20 km around each village. The 10 km MarinePPI value was used as the main population proximity indicator, while the 20 km value was retained for sensitivity checks.

Village-level spatial data were also used to support the coding of environmental and land–sea context variables. Mangrove presence was included as a natural-capital asset

because mangroves can provide shoreline protection, trap sediments, buffer coastal nutrient flows and support adjacent coastal ecosystems, including seagrass (Lee et al. 2014). Aquaculture pond presence was included as a potential exposure indicator because shrimp or aquaculture ponds may indicate land-to-sea pressure through nutrient loading, effluent discharge, salinity alteration or coastal land-use change, such as the conversion of mangroves (Primavera 2006; Van Wesenbeeck et al. 2015; Thomsen et al. 2020). These variables were treated as village-level indicators rather than direct ecological measurements of seagrass condition.

In addition to MarinePPI, we also calculated internal population proximity metrics based on distances among surveyed villages. For each village, we calculated the population of nearby surveyed villages within distance bands and a simple population gravity metric, although this differed from the metric used by Cinner et al. (2018). These internal proximity measures were not used as the primary population-pressure metric but were retained as sensitivity checks because they provide a transparent way to evaluate local clustering among surveyed fishing villages.

Variable selection and vulnerability framework

Following data cleaning, household and village variables were grouped into indicators of exposure, sensitivity and adaptive capacity. This structure follows widely used vulnerability frameworks in coastal social–ecological systems, where vulnerability is understood as a function of the stressors people or places are exposed to, the degree to which they are sensitive to those stressors, and their capacity to respond or adapt (Adger 2006; Cinner et al. 2013). The adaptive capacity indicators were also informed by previous vulnerability frameworks, which emphasise that adaptive capacity is multidimensional and includes assets, flexibility, social organisation, learning and agency, rather than simply income or infrastructure (Cinner, et al. 2018).

Indicators were selected to reflect the available household and village data, their relevance to seagrass-dependent fishing livelihoods, and their interpretability for local management. We treated the analysis as an assessment of potential vulnerability, rather than observed vulnerability, because we do not include before–after measurements of seagrass decline, or household welfare change.

Exposure indicators captured pressures that may increase risk to seagrass social-ecological systems. These included; aquaculture pond presence, reported trawl-net challenges, boats per household, mechanised boat share, and MarinePPI population proximity. Aquaculture ponds and trawl-net challenges were coded as binary indicators. Boat pressure was calculated as the number of boats per 100 households. Mechanised boat share was calculated as the proportion of total village boats that were mechanised. MarinePPI was used as a proxy for wider population pressure or market proximity around each village.

Sensitivity indicators captured the degree to which households may be affected if seagrass-associated fishing livelihoods are disrupted. These included whether fishing was the main household livelihood, livelihood diversity, total income, family size and housing condition. Households reporting fishing as their primary livelihood were coded as more sensitive because the vast majority of fishing households in the region fish in seagrass meadows or catch seagrass-associated species (Jeyabaskaran et al. 2018; Balaji et al. 2025). Fewer livelihoods, lower income, larger family size and weaker housing condition were also interpreted as increasing household sensitivity.

Adaptive capacity indicators captured the ability of households and villages to cope with, respond to or buffer the effects of change. At the household level, boat ownership and livelihood diversity were included as adaptive capacity indicators. At village level, adaptive capacity indicators represented learning infrastructure, public assets, social organisations and natural capital assets. These included schools, ration depots, water infrastructure, health centres, public toilets, community halls, disaster centres, women's self-help groups, youth clubs, fishnet centres, fishing societies, livestock and mangrove presence. Fishing societies, women's groups and youth clubs were treated as indicators of social organisation or agency. Schools were treated as learning infrastructure. Health centres, water infrastructure, public toilets, ration depots, community halls and disaster centres were treated as public or physical assets. Mangroves were treated as a natural-capital asset.

For analysis, all continuous indicators were placed on a common 0 to 1 scale using min-max normalisation. For indicators where higher raw values represented lower vulnerability, reverse normalisation was used. For example, higher income and greater livelihood diversity reduce sensitivity, so these were reverse-coded when included in the sensitivity score. Binary variables were coded as 0 or 1. Housing condition was coded as an ordinal sensitivity indicator, with weak housing assigned the highest sensitivity score, old housing assigned an intermediate score, and good housing assigned the lowest sensitivity score. Composite scores were calculated using the mean of available indicators so that households or villages with partial missing data could still be retained where sufficient information was available.

Household sensitivity and adaptive capacity

For each household, we calculated a core household sensitivity score using five indicators: fishing as the primary livelihood, livelihood concentration, low income, family size and housing condition. The score was calculated as the mean of these indicators:

$$HS_i = \frac{F_i + LC_i + LI_i + FS_i + H_i}{n_i}$$

where HS_i is the household sensitivity score for household i, F_i is fishing-primary livelihood, LC_i is livelihood concentration, LI_i is low income, FS_i is family-size burden, H_i

is housing condition, and n_i is the number of non-missing indicators included in the score for household i.

We also calculated a household adaptive capacity score using boat ownership and livelihood diversity:

$$HAC_i = \frac{B_i + LD_i}{n_i}$$

where HAC_i is household adaptive capacity for household i, B_i is boat ownership, LD_i is livelihood diversity, and n_i is the number of non-missing adaptive capacity indicators. Boat ownership was treated as a productive asset, while recognising that it may also indicate stronger dependence on fishing.

Household scores were then aggregated to the village level. For each village, we calculated the mean household sensitivity score, the proportion of households reporting fishing as their primary livelihood, the mean household adaptive capacity score, the proportion of households owning boats, median income, and mean number of livelihoods. These summaries allowed household-level vulnerability patterns to inform the village-level analysis.

Village exposure, sensitivity and adaptive capacity scores

For each village, exposure was calculated as the mean of the normalised exposure indicators:

$$E_v = \frac{AQ_v + TR_v + BP_v + MB_v + PPI_v}{n_v}$$

where E_v is village exposure, AQ_v is aquaculture pond presence, TR_v is trawl-net challenge, BP_v is boat pressure, MB_v is mechanised boat share, PPI_v is MarinePPI population proximity, and n_v is the number of available exposure indicators for village v.

Village sensitivity was calculated using the mean household sensitivity score and the proportion of fishing-primary households:

$$S_v = \frac{\underline{HS_v} + PF_v}{n_v}$$

where S_v is village sensitivity, $\underline{HS_v}$ is mean household sensitivity in village v, PF_v is the proportion of households reporting fishing as the primary livelihood in village v, and n_v is the number of available sensitivity indicators.

Village adaptive capacity was calculated as the mean of household, infrastructure, social organisation and natural-capital indicators:

$$AC_v = \frac{1}{n_v} \sum_{k=1}^{n_v} AC_{vk}$$

where AC_v is village adaptive capacity for village v, AC_{vk} is adaptive capacity indicator k for village v, and n_v is the number of available adaptive capacity indicators. Indicators included boat ownership, livelihood diversity, schools, ration depot, water infrastructure, health centres, public toilets, community hall, disaster centre, women's groups, youth clubs, fishnet centres, fishing societies, livestock and mangrove presence.

Vulnerability scoring

Finally, we calculated potential vulnerability using a multiplicative index:

$$V_v = E_v \times S_v \times (1 - AC_v)$$

where V_v is potential vulnerability for village v, $E_v$is exposure, S_v is sensitivity and AC_v is adaptive capacity.

We used this multiplicative formula rather than a simple additive formula (Hahn et al. 2009) or the averaged additive version. This approach is more conservative and better reflects the idea that high vulnerability occurs where high exposure, high sensitivity and low adaptive capacity occur together. In an additive index, high values in one component can compensate for low values in another. For example, a village with high exposure but low sensitivity could still receive a high vulnerability score. In contrast, the multiplicative index gives high scores only where the components coincide.

The multiplicative formulation has also been used in similar studies to assess fishery-based livelihood vulnerability among coastal fishing households in Bangladesh after normalising exposure, sensitivity and adaptive capacity to a common scale (Islam, et al. 2014). This approach is consistent with social–ecological vulnerability thinking in which vulnerability emerges from the interaction among stress exposure, livelihood dependence and the capacity to adapt, even if the formulas used are somewhat different (Cinner, et al. 2013; Cinner, et al. 2018).

We therefore used the multiplicative index as the primary vulnerability score because the aim was to identify villages where pressure on seagrass-fishing systems, household sensitivity and limited adaptive capacity overlap. The raw vulnerability score was then rescaled between 0 and 1 to support comparison among villages

Management typology

To make the results more useful for management, villages were also classified into a four-part management typology based on exposure and adaptive capacity (Table 1). Median exposure and median adaptive capacity were used as relative thresholds, where villages were classified as having higher or lower exposure and higher or lower adaptive capacity. This typology was treated as a key management output because it identifies

different intervention pathways, rather than simply ranking villages from highest to lowest vulnerability.

Table 1. Management typologies used.

Management typology	Exposure	Adaptive capacity	Description
Priority support sites	High	Low	These villages face relatively high pressure and have fewer resources or institutions to cope with change.
Co-management opportunity sites	High	High	These villages face pressure but have stronger existing assets, institutions or organisation that could support co-management.
Preventative support sites	Low	Low	These villages are not currently among the most exposed, but may be poorly prepared if pressures increase.
Stewardship or learning sites	Low	High	These villages have lower relative exposure and stronger adaptive capacity, and may provide opportunities for locally led stewardship or peer learning.

Sensitivity checks

We also tested whether village rankings were robust to alternative assumptions in the vulnerability index. Six versions of the index were compared. The first was the core multiplicative index. The second removed MarinePPI to test whether external population proximity was driving the rankings. The third removed mangrove presence from the adaptive capacity score to test whether the natural-capital asset indicator strongly influenced outcomes. The fourth used the extended household sensitivity score, which included additional household concern variables. The fifth used only local pressure indicators in the exposure score, excluding wider population proximity. The sixth used an additive vulnerability formulation rather than the multiplicative formulation.

For each version, villages were ranked from highest to lowest vulnerability. We then calculated the mean rank, rank variation and the proportion of index versions in which each village appeared in the top four. This allowed us to identify villages that remained high-priority across alternative assumptions, and to distinguish robust management priorities from villages whose ranking depended more strongly on methodological choices.

Results

Seagrass-fishing dependence was widespread across surveyed households

The household survey captured 247 households across villages in the Palk Bay region. Of these, 221 households reported fishing as their primary livelihood, representing almost nine out of every ten surveyed households. Across the 13 villages with matched household and village-level data, the mean proportion of fishing-primary households was 91.7%, although dependence varied among villages from 63.6% in Velivayal to 100% in Anthoniyapuram, Adaikkdevan, Kazhumanguda, Kollukkadu, Keezhakudiyiruppu and Manthiripattinam.

Fishing-primary households were more sensitive to change than households with other primary livelihoods. Their mean household sensitivity score was 0.630, compared with 0.456 for households reporting other primary livelihoods. This difference reflects the structure of the sensitivity index, which captures dependence on fishing, low livelihood diversity, low income, household size and housing condition. However, fishing-primary households also had higher mean adaptive capacity than non-fishing-primary households (0.483 vs 0.160), largely because they were more likely to own productive fishing assets.

Livelihood diversification was limited among sampled households. Single-livelihood households made up the majority of the sample and had higher sensitivity than households with multiple livelihoods (0.622 vs 0.587). They also had lower adaptive capacity (0.405 vs 0.554) and lower median income (6,000 vs 9,000) than multiple livelihood households. The lowest-income quartile had slightly higher sensitivity than higher-income households (0.636 vs 0.603) and lower adaptive capacity (0.394 vs 0.464). These patterns indicate that household sensitivity is socially differentiated, with the highest sensitivity concentrated among households that combine fishing dependence, low income and limited livelihood flexibility.

Boat ownership showed a more complex pattern within adaptive capacity and sensitivity than other indicators. Boat-owning households had much higher adaptive capacity than non-boat-owning households (0.716 vs 0.217) and higher median income (10,000 vs 5,500), but their mean sensitivity was also slightly higher (0.629 vs 0.596).

Villages separated into four management-relevant vulnerability types

Village-level vulnerability was not evenly distributed across Palk Bay. The 13 matched villages separated into four management types based on their relative exposure and adaptive capacity (Figure 1).

Three villages were classified as priority support sites, combining higher exposure with lower adaptive capacity (Anthoniyapuram, Keezhathottam and Velivayal). These villages represent places where pressure on seagrass-fishing systems is relatively high, while the

capacity to absorb or respond to change is more limited. Anthoniyapuram had the highest overall potential vulnerability score in the analysis (1.000), followed by Keezhathottam (0.789). Velivayal also fell within this category, although its overall vulnerability score was lower (0.447) because its household fishing dependence and sensitivity were lower than in other high-exposure villages.

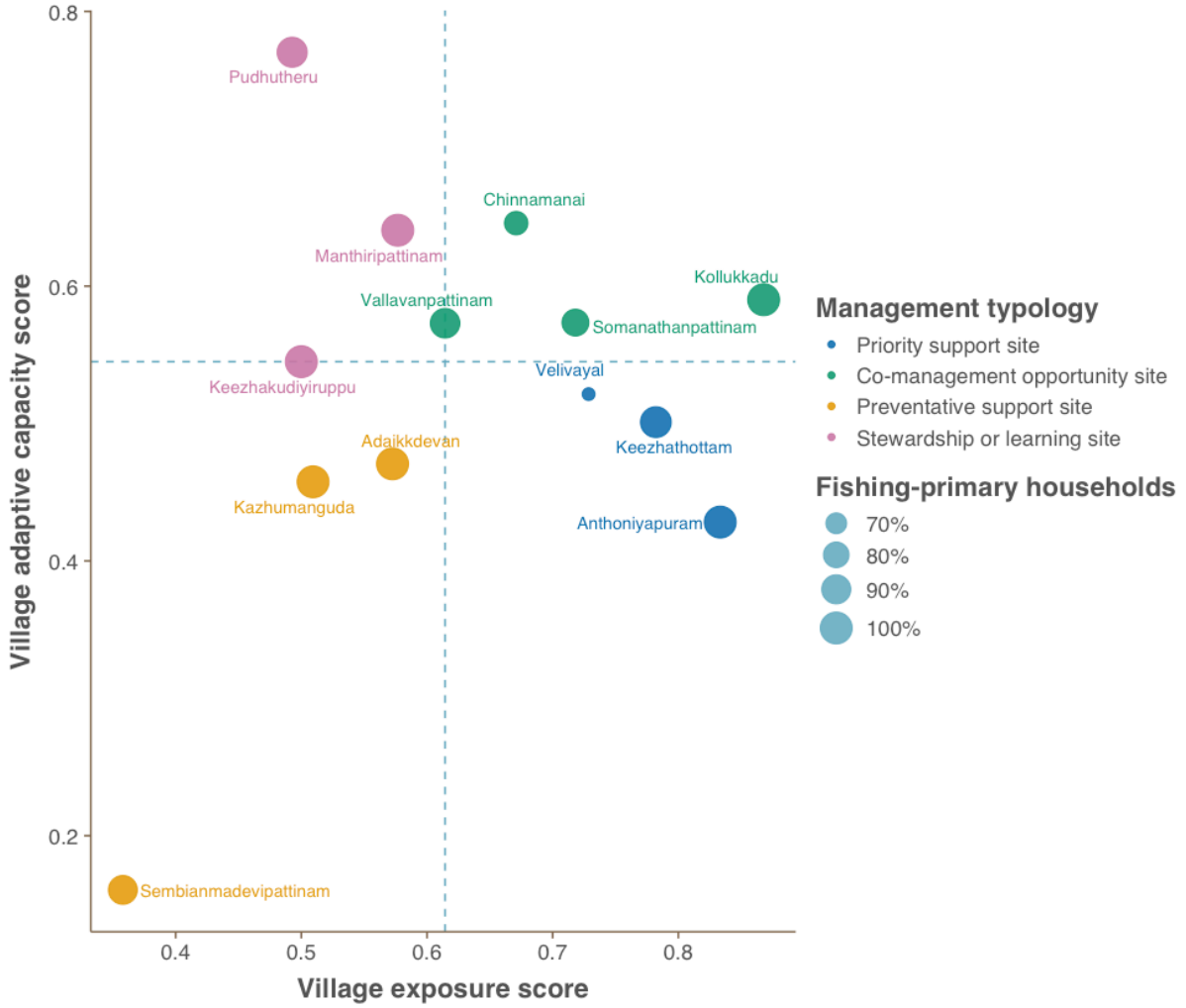


Figure 1. Place-based/context specific management pathways emerge from differences in village exposure and adaptive capacity. Villages are plotted according to their standardised exposure and adaptive capacity scores (0–1). Median values (dashed lines) divide villages into four management typologies representing priority support, co-management opportunities, preventive support, and stewardship or learning sites. Point size indicates the proportion of surveyed households reporting fishing as their primary livelihood.

Four villages were classified as co-management opportunity sites, combining higher exposure with higher adaptive capacity (Kollukkadu, Somanathanpattinam, Vallavanpattinam and Chinnamanai). We found that these villages face relatively high exposure, but also have stronger adaptive-capacity conditions, such as social institutions, infrastructure, household assets, or natural-capital buffers (e.g., mangroves). Kollukkadu had the third-highest potential vulnerability score overall (0.725), indicating that strong capacity does not eliminate vulnerability where exposure

and sensitivity remain high. However, this category suggests that management may be able to build on existing capacity through co-management, fisher-led monitoring and local stewardship.

Three villages were classified as preventive support sites, combining lower exposure with lower adaptive capacity (Adaikkdevan, Kazhumanguda and Sembianmadevipattinam). These villages were not the most exposed, but their lower adaptive capacity means they may be less prepared if seagrass-fishing pressures intensify or livelihood returns decline in the future. Sembianmadevipattinam was particularly distinctive because it had the lowest adaptive capacity score in the dataset (0.161) and was the only village classified as primarily low-capacity-driven. This indicates a different intervention pathway from villages where vulnerability is mainly driven by exposure.

We also identified three villages as potential stewardship or learning sites, combining lower exposure with higher adaptive capacity (Keezhakudiyiruppu, Manthiripattinam and Pudhutheru). These villages had lower potential vulnerability scores, particularly Pudhutheru, which had the lowest scaled vulnerability score (0.000) due to its relatively high adaptive capacity (0.770) and lower exposure (0.493). These villages may provide opportunities for peer learning, stewardship approaches or locally led monitoring, provided that lower exposure is not interpreted as absence of future risk.

Exposure, sensitivity and adaptive capacity varied independently

The three dimensions of vulnerability varied. Village exposure scores ranged from 0.358 to 0.868, sensitivity from 0.620 to 0.838, and adaptive capacity from 0.161 to 0.770, showing that potential vulnerability was not determined by any single component (Figure 2).

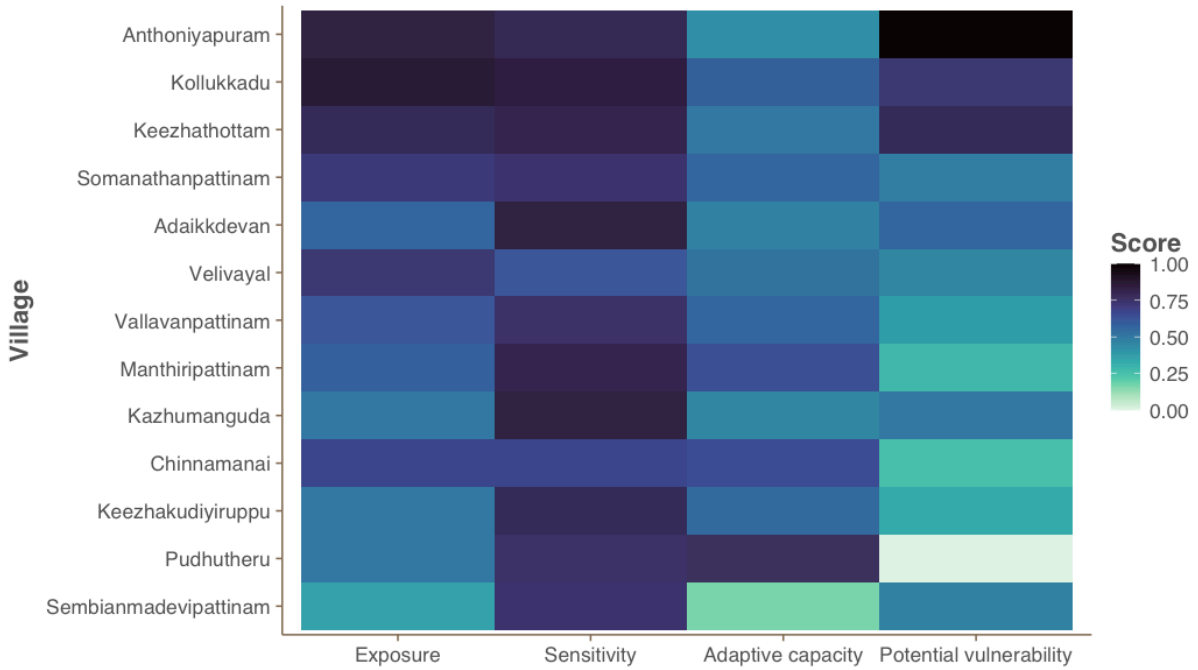


Figure 2. Spatial variation in the components of village vulnerability across seagrass-dependent fishing communities in Palk Bay, India. Heatmap showing relative village scores for exposure, household sensitivity, adaptive capacity and the resulting potential vulnerability index. All indices were standardised to a common scale (0–1), where darker shading indicates higher relative values for that dimension. Potential vulnerability was calculated using a multiplicative index, identifying villages where high exposure and household sensitivity coincide with low adaptive capacity. Scores are relative within the study region and should not be interpreted as absolute measures of vulnerability.

Some villages combined high exposure with high sensitivity. Kollukkadu, for example, had the highest exposure score (0.868) and one of the highest sensitivity scores (0.838), but also relatively high adaptive capacity (0.590). This placed it in the co-management opportunity category rather than the highest-priority support category. By contrast, Anthoniyapuram had similarly high exposure (0.833) and high sensitivity (0.796) but lower adaptive capacity (0.428), producing the highest potential vulnerability score overall.

Other villages had high sensitivity but lower exposure. Adaikkdevan and Kazhumanguda both had 100% fishing-primary households and high sensitivity scores (0.837 and 0.833, respectively), but lower exposure scores (0.573 and 0.509). Their vulnerability is therefore less about immediate pressure and more about livelihood dependence combined with limited capacity to respond to change in the future. These villages may require preventive support rather than immediate pressure-reduction interventions.

Adaptive capacity also varied independently of household sensitivity. Pudhutheru had relatively high sensitivity (0.748) but the highest adaptive capacity score (0.770) and a low exposure score (0.493), resulting in the lowest potential vulnerability score. Sembianmadevipattinam had lower exposure (0.358) and moderate sensitivity (0.738), but very low adaptive capacity (0.161), making low capacity the dominant vulnerability

driver. These findings highlight why exposure alone is insufficient for identifying management priorities.

Different villages were vulnerable for different reasons

We then decomposed drivers to show that vulnerability was not produced by a single mechanism across all villages (Figure 3). Most villages were sensitivity-driven (Keezhathottam, Adaikkdevan, Kazhumanguda, Somanathanpattinam, Vallavanpattinam, Keezhakudiyiruppu, Manthiripattinam, Chinnamanai and Pudhutheru), meaning that household dependence, income, livelihood concentration and other household conditions contributed most strongly to their vulnerability profile.

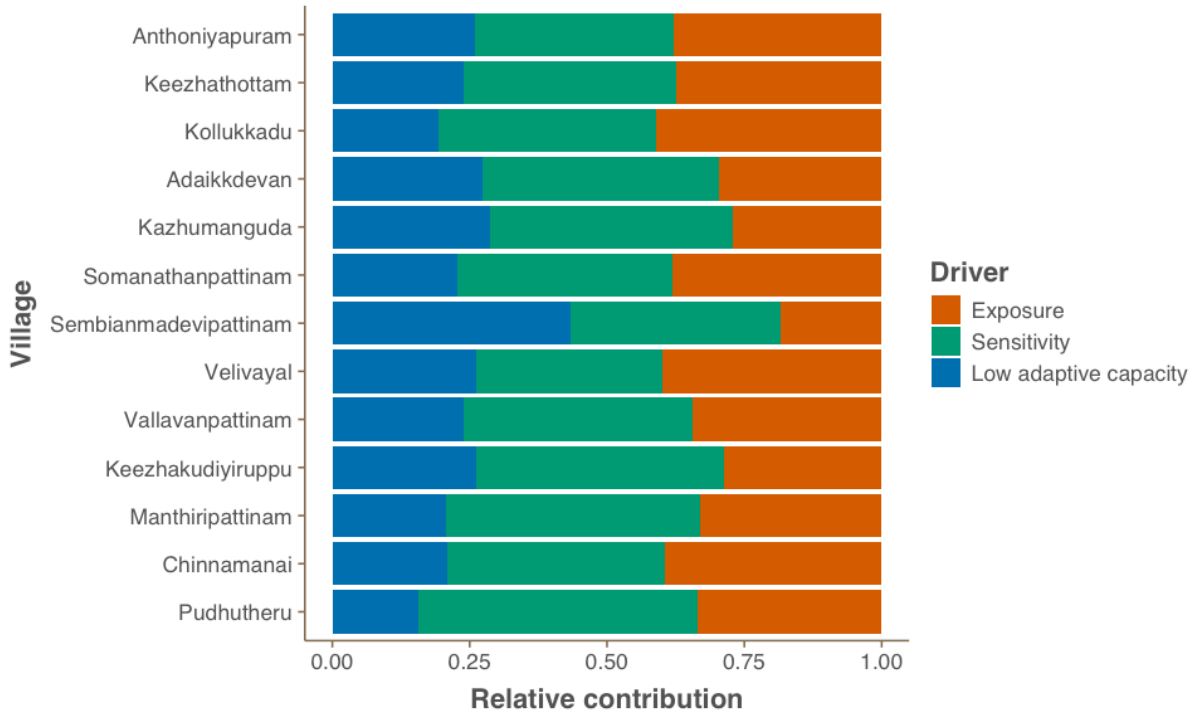


Figure 3. Relative contribution of exposure, household sensitivity and low adaptive capacity to potential vulnerability across seagrass-dependent fishing villages. Stacked bars show the proportional contribution of each vulnerability dimension to the overall vulnerability profile of each village. Contributions were calculated by standardising exposure, sensitivity and inverse adaptive capacity, so that their relative influence summed to one for each village.

However, three villages were exposure-driven (Anthoniyapuram, Kollukkadu and Velivayal). These villages had relatively high contributions from exposure indicators such as aquaculture ponds, trawl-net challenges, boat pressure, mechanised boat share and population proximity. In Anthoniyapuram, exposure contributed 37.9% of the vulnerability profile, compared with 36.2% from sensitivity and 26.0% from low adaptive capacity. In Kollukkadu, exposure was also the largest component (41.0%), followed

closely by sensitivity (39.6%). Velivayal was similarly exposure-driven, with exposure contributing 39.9%.

Only one village, Sembianmadevipattinam, was low-capacity-driven. In this village, low adaptive capacity contributed 43.4% of the vulnerability profile, compared with 38.1% from sensitivity and 18.5% from exposure. Importantly, this shows that not all vulnerable villages require the same kind of intervention. Where vulnerability is exposure-driven, reducing pressure on seagrass-fishing systems is likely to be central. Where vulnerability is sensitivity-driven, household livelihood support, welfare buffers and livelihood flexibility become more important. Where vulnerability is low-capacity-driven, investment in institutions, infrastructure and collective organisation may be the most relevant entry point.

Priority rankings were broadly robust to alternative index assumptions

Sensitivity analyses showed that several village priorities were stable across alternative vulnerability indexes (SUpplimentary). Anthoniyapuram and Keezhathottam were the most robust high-priority villages. Both appeared in the top four priority villages across all six index versions. Anthoniyapuram had a mean rank of 1.17 and a high-priority consistency score of 1.00, while Keezhathottam had a mean rank of 2.83 and a high-priority consistency score of 1.00.

Adaikkdevan and Kollukkadu were also relatively robust, appearing in the top four in four of the six index versions. Sembianmadevipattinam was more assumption-sensitive. It ranked first under the additive index and third under versions excluding MarinePPI or using local pressure only but ranked seventh in the core multiplicative index. This reflects the village's very low adaptive capacity but lower exposure, showing that it becomes more prominent when low capacity is allowed to dominate the vulnerability score.

Other villages were less consistently high-ranking. Somanathanpattinam, Kazhumanguda and Velivayal occupied intermediate positions, while Vallavanpattinam, Keezhakudiyiruppu, Manthiripattinam, Chinnamanai and Pudhutheru remained lower-priority across most index versions. Pudhutheru was the most stable low-vulnerability village, ranking last under all six index versions.

We argue that these findings support the use of the vulnerability typology alongside ranked scores; rankings identify priority villages, while the typology indicates the kind of management response that may be most appropriate.

Household sensitivity was socially differentiated

Moving back to household level data, we found that sensitivity was not evenly distributed. Fishing-primary households had higher sensitivity than households with other primary livelihoods, but they also had higher adaptive capacity.

Livelihood diversity emerged as one of the clearest household-level differentiators. Households with multiple livelihoods had lower sensitivity (0.587) and higher adaptive capacity (0.554) than single-livelihood households, which had higher sensitivity (0.622) and lower adaptive capacity (0.405).

Income also differentiated household sensitivity. The lowest-income quartile had higher sensitivity (0.636) and lower adaptive capacity (0.394) than higher-income households, which had sensitivity of 0.603 and adaptive capacity of 0.464. However, the relationship between income and sensitivity was not strictly linear. Sensitivity was highest among many low- to middle-income fishing households and lower among some higher-income households, but with substantial variation.

There was also a duality to boat ownership. Boat-owning households had higher adaptive capacity and higher median income, but their sensitivity was not lower than that of non-boat-owning households.

Discussion

Key system insights

Amidst converging global biodiversity and climate crises, place-based understandings of the social dimensions of social-ecological systems are essential for identifying how environmental change shapes human well-being, livelihood opportunities, and ecosystem persistence (Bennett et al. 2021). Here, we examine the social vulnerability of 247 coastal households and 13 villages engaged in seagrass-associated fisheries across Tamil Nadu region of Palk Bay, and identified potential localised management pathways to build local socio-ecological resilience and enhance seagrass condition. We reveal that social vulnerability is heterogeneous among seagrass-dependent households and villages. Variability in vulnerability was socially differentiated and driven by relationships between bottom-line dependence on seagrass resources for livelihoods, household capital and assets, surrounding public assets, learning infrastructure and social organisations. The variations in village sensitivity and adaptive capacity to seagrass SES pressures highlight opportunities for place-based management and provide insights into pathways to reduce vulnerability and strengthen local resilience.

Socially differentiated household vulnerability

We found that household vulnerability was socially differentiated; sensitivity and the adaptive capacity of households to potential change in seagrass condition differed in accordance with their dependence on fishing as a livelihood, livelihood diversity, income, and fishing-associated asset ownership. These findings are analogous with studies on reef-associated fisheries which reveal trade-offs between specialisation and

financial asset investment in fishing gears generating higher income and efficiency, but reduced ability to adapt (Cinner et al. 2013).

Within the Palk Bay seagrass-associated SES, sensitivity and adaptive capacity were not evenly distributed across households. Fishing-primary households had higher sensitivity, but also higher adaptive capacity compared with households relying on other primary livelihoods. This reflects a key trade-off in seagrass systems where fishing dependent households often possess greater fishing related assets and skills, but these assets are tied to the same social-ecological system that may itself be at risk from social and environmental change (Jones et al. 2022; Jones et al. 2022; Jones et al. 2026). As a result, household livelihood diversification/occupational multiplicity may provide an important buffering role against the risks and disruptions to seagrass-associated fishing livelihoods. Our analysis supports this idea. We show that households engaged in multiple livelihoods had lower sensitivity and higher adaptive capacity than single-livelihood households. Therefore, occupational multiplicity facilitates risk distribution, allowing households to absorb environmental, social, and economic shocks and to adapt more easily when one livelihood is affected by change (Cinner et al. 2009; Daw et al. 2012).

Boat ownership introduces a complex and important duality within seagrass-fishing households. The adaptive capacity of households owning a boat was greater than households without such an asset. This was also the case for median household income. However, household sensitivity was not lower than that of non-boat owners. This suggests that boat ownership provides productive capacity (e.g., opportunity to fish elsewhere) but may also indicate stronger dependence on fishing as a livelihood strategy (Jones et al. 2022). In practical terms, households with boats may have more options within the associated fishery and increased adaptive capacity, but they may also carry higher exposure to any decline in seagrass-associated fisheries species or conditions. Their assets, income and occupational identity are more tightly linked to fishing, and investments in boats and fishing gear represent specialised physical capital whose value depends largely on the continued viability of the fishery, limiting opportunities to recover investments through livelihood transitions (Allison and Ellis 2001; Cinner et al. 2009; Cinner et al. 2013).

There was substantial variation in the relationship between household income and sensitivity. In general, household sensitivity was highest among many low- to middle-income fishing households and lower among some higher-income households, however, these patterns were highly variable. Revealing these non-linear relationships reinforces the need to understand vulnerability as a combination of income, livelihood dependence, household structure and assets, rather than leaning solely an indicator of poverty. Our findings align with the multidimensional conceptualisations of vulnerability and poverty, which include complex interactions between human-wellbeing and the

591 natural environment which extend beyond measures of income (Béné et al. 2009; Daw et
592 al. 2016; Schleicher et al. 2025).

593 **Exposure and sensitivity driven village vulnerability**

594 The relationships between household and village vulnerability are mutually reinforcing,
595 where household vulnerability is embedded within the broader context of village
596 vulnerability. Village-level characteristics shape the vulnerability of individual
597 households, while aggregated household vulnerability contributes to the vulnerability of
598 the village. The ways in which the dimensions of vulnerability are represented within a
599 vulnerability profile are therefore contextual and non-linear (Turner et al. 2003; Adger
600 2006).

601 Across the studied villages, the three dimensions of vulnerability were highly variable,
602 meaning that potential vulnerability was not determined by any single component
603 (exposure, sensitivity, adaptive capacity). Village vulnerability profiles were driven by
604 sensitivity indicators in nine villages, exposure indicators in three villages, and adaptive
605 capacity indicators in one village. This variation in vulnerability profiles highlights that
606 combinations of different interacting dimensions drive vulnerability and suggests that a
607 multiplicity vulnerability index is most relevant to this context. This necessitates
608 differentiated interventions that target the specific drivers and reinforcing mechanisms
609 of vulnerability that operate in particular households and villages within seagrass SES.

610 **Place-based pathways for resilience building**

611 To address these variations in vulnerability profiles, the four resilience pathways were
612 developed to provide an initial basis for considering management options. Rather than
613 prescribing uniform interventions, these pathways intend to support deliberation and
614 context specific decision making. The proposed pathways recognise that vulnerability
615 profiles coexist across land/seascapes, that support needs to be socio-culturally
616 differentiated, that embedded community-based governance is vital for effective natural
617 resource management, and that pathways are understood as complementary, each
618 holding distinct considerations for management planning. Pathways categorisation
619 adopted a multi-dimensional indexing, recognising that vulnerability is determined by
620 various, interplaying factors (Adger 2006; Birkmann 2006; Gunaratne et al. 2023)

621 *Priority support* was proposed for villages experiencing high pressure on seagrass
622 ecosystems and seagrass-associated resources, and that have limited resources,
623 infrastructure or social organisations to respond to changes in seagrass condition or
624 ongoing ecosystem loss. Priority support in these contexts could help to strengthen
625 social adaptive capacity by supporting locally led decisions for infrastructure, assets,
626 resource distribution and condition, whilst also addressing acute ecosystem threats to
627 promote seagrass meadow protection. The extent, and type, of support required should
628 vary according to specific local circumstances, recognising the heterogeneity of local

ecosystem pressures and village infrastructures. Inclusive community participation, particularly with women, should be embedded within priority support to promote the community-led and equitable distribution of any social and economic benefits realised from the approach (Brooks et al. 2012; Le et al. 2026).

The second potential pathway is to build *co-management opportunities*. Villages in this typology face substantial pressures associated with seagrass condition and resource availability, but have some existing assets, infrastructure and community organisations to support adaptions to change. Building on the existing capacity through embedded community governance may help align local knowledge, village priorities, existing responsibilities, livelihoods, cultural values and enforcement mechanisms to create flexible, context-specific responses to ecosystem change. Co-management represents a potential mechanism for enhancing adaptive capacity, driven by local-decision making structures, knowledge, and stewardship. Examples of Indigenous-led management of customary fishing ground closures integrate local knowledge and village stewardship with science and policy to create flexible responses to fishing and climate change. Adoption and spread of such management strategies occur most readily through spatial nearest neighbours, and are influenced by village social structure, local conflict, the presence of supporting organisations and district management committees, and the degree of community trust in the government (Mills et al. 2019; Jagadish et al. 2024). Such examples provide valuable learnings for Indigenous or locally led natural resource management.

Preventative support is the third pathway proposed for villages currently not facing substantial pressure on the local seagrass social-ecological system but are poorly prepared to adapt if seagrass condition and resources deteriorate or if pressures increase. Pre-empting some of the challenges associated with safeguarding seagrass SES, preventative support could include building skills, knowledge, and organisational capacity, establishing seagrass monitoring to identify early signs of change, strengthen local governance and institutions, support livelihood diversification to alleviate backstop reliance on seagrass resources. By proactively investing in community to close capacity gaps, build capability and competency, this pathway could enhance preparedness under changing environmental conditions.

The fourth pathway considers villages with low exposure to pressures and high adaptive capacity as *stewardship or learning sites*. These sites focus on maintaining ecological integrity and safeguarding social systems that are currently functioning effectively. Rather than responding to acute seagrass losses and degradation or community capacity deficits, a stewardship site champions protection, conservation, poverty mediation, food security, continued stewardship of seagrass associated resources, monitor emergent change, and reinforce governance approaches which contribute to positive social and ecological outcomes. Peer learning from neighbouring villages can

promote the spread of appropriate local management strategies (Lewis-Brown et al. 2025).

These pathways should be viewed as conceptual interpretations of the vulnerability patterns identified through this work to build toward resilience solutions, rather than definitive management prescriptions. These conceptualisations highlight opportunities for considering future management that could be tailored to specific, local seagrass-associated coastal communities. Recognising the heterogeneity of social vulnerability in seagrass-associated fisheries, this approach provides a basis for future research and dialogue on how management might align with local values, ecology, capacities, cultures, decision-making structures.

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Author contributions

L.C., B.J., and B.V. conceived the study. G.S., O.F., S.S., and B.V. collected data. B.J. and L.C. analysed the data and wrote the first draft of the manuscript. All authors contributed to writing and editing the final manuscript.

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