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Human dimensions of harmful algal blooms in coastal Peru: perceived impacts, adaptation, and governance challenges

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Harmful algal blooms (HABs) can cause marine fauna mortality, human health risks, and fishery closures, thereby threatening coastal livelihoods. Despite increasing frequency and severity of HABs under climate-related and anthropogenic pressures, their social, economic, and political impacts remain understudied, especially in Latin America. To address this gap, this study explored the social-ecological dynamics of HABs in coastal Peru through 17 participatory workshops with mariculture producers, fishers, scientists, and public officials connected to the bays of Sechura and Paracas. Using fuzzy cognitive mapping, the study identified key perceived drivers, impacts, adaptation strategies, and barriers to adaptation, revealing shared understandings, but also important differences in how stakeholders interpret HABs and respond to them. We found that the most important impacts perceived were not public health effects, but losses in production, income, and employment, especially in mariculture and related coastal activities. The findings also reveal technological, information-related, and institutional disparities that make small-scale producers more vulnerable to HAB impacts compared to larger firms, potentially reinforcing existing inequalities. Simulations of proposed adaptation strategies highlighted the importance of early warning systems, emergency protocols, intersectoral coordination, and public awareness in strengthening coastal resilience in the face of HABs. Overall, the study shows that HABs in Peru are not only an ecological issue, but also a matter of unevenly distributed impacts and adaptive capacities, highlighting the need for more inclusive and equitable HAB governance.

KEYWORDS
adaptation, coastal livelihoods, fuzzy cognitive map (FCM), governance, mariculture, Peru, social-ecological system, socioeconomic impacts

1 Introduction

HABs are recognized as a major challenge for coastal social-ecological systems (SES) around the world (Anderson et al., 2012; Hallegraeff, 2021). Although HABs are natural phenomena involving rapid increases in the abundance of microalgae and cyanobacteria, they can cause ecological disruption and socio-economic losses through oxygen depletion, toxins, other harmful metabolites, or water discoloration (Hallegraeff, 2021; Lehman et al., 2021). These processes threaten coastal livelihoods by causing marine fauna mortality, health risks, fishery and aquaculture closures, or by undermining tourism and recreational activities (Berdalet et al., 2016; Carias et al., 2024). Economic losses in mariculture alone have been estimated at US$ 8 billion per year (Brown et al., 2020). HAB-related costs are expected to rise as blooms become more frequent and severe under climate-related and anthropogenic pressures, although the growing number of reported blooms also reflects improved monitoring and reporting (Hoagland et al., 2002; Anderson et al., 2015; Wurtsbaugh et al., 2019; Hallegraeff et al., 2021; Dai et al., 2023), as well as the expansion in the scale and nature of societal impacts (Hallegraeff et al., 2021). These trends raise questions about the resilience of diverse coastal actors and the adequacy of institutions to respond to HABs. Moreover, human drivers and social impacts underscore the need to study HABs from an integrated social-ecological system perspective. HABs are shaped by ecological and biophysical dynamics while also having political, economic, and socio-cultural implications that influence perceptions, practices, and governance, making a social-ecological perspective well-suited to study prevention, control, mitigation, and adaptation (Berdalet et al., 2016; Van Dolah et al., 2016; McKinley et al., 2024).

Yet, the social and human dimension of HABs continues to be understudied (Bauer et al., 2010; Berdalet et al., 2016; McKinley et al., 2024). While HAB-related research has expanded over the past decades, it remains dominated by biological and physical studies and monitoring-focused work. This is particularly true in Latin America, where much of the literature focuses on (1) identifying and documenting which HAB-causing species occur and under what environmental conditions, (2) investigating toxin production in some species, (3) assessing ecosystem impacts (Kahru et al., 2004; Sanchez et al., 2017; Cuellar-Martinez et al., 2018; López-Cortés et al., 2019; Müller et al., 2020; Hallegraeff, 2021; Tenorio et al., 2021, 2026; Cueto-Vega et al., 2022). By contrast, empirical work on socio-economic consequences, community risk perception, and adaptation pathways remains scarce, despite the dependence of many coastal communities on marine resources and their vulnerability to abrupt environmental change (Kluger et al., 2019a; Billi et al., 2022; Kriegl et al., 2022; Carias et al., 2024). Instead, HABs social-science research is concentrated in a set of high-income settings – most notably the U.S. West Coast and Florida (Larkin and Adams, 2007; Backer, 2009; Ritzman et al., 2018; Moore et al., 2020). Moreover, many studies have a narrower focus on either direct economic impacts, risk perception, or health issues (McKinley et al., 2024). Nevertheless, a small but growing body of social-science research has examined social dimensions of HABs in Latin America and other Global South contexts. These include studies on red tide risk perception among coastal communities and authorities in Ecuador (Borbor-Córdova et al., 2018), community perceptions of HAB-related socio-economic impacts in Vietnam (Kapitsinis et al., 2025) and local ecological knowledge of harmful macroalgal events in Mexico and the Caribbean (Rosellón-Druker et al., 2023; Hamel et al., 2024, Hamel et al., 2026). These studies show that local actors often understand bloom impacts through environmental and economic wellbeing, and they underline the value of incorporating local risk perceptions into resource management. In Chile, research has further examined the political dimensions of HABs, including communication dynamics during HAB crises as well as political conflicts over meaning-making and governance responses in a context shaped by industrial salmon aquaculture (Arriagada et al., 2025; Billi et al., 2022; Cabello et al., 2018; Mascareño et al., 2018).

Notably, however, there are no social-ecological case studies of HABs in the Humboldt Current upwelling system, despite its importance as one of the most productive fishing areas with great socio-economic significance (Mendo et al., 2016). Moreover, major gaps remain in our understanding of the distributional and equity implications of HABs (McKinley et al., 2024), despite growing concerns for equity and justice issues in the ocean economy more broadly (Bennett et al., 2021; Blythe et al., 2023). Consequently, there is a need to understand how HAB impacts are unevenly distributed across social groups and places to ensure governance interventions do not deepen existing inequalities (Jardine et al., 2020; McKinley et al., 2024).

This paper responds to the need to strengthen social science and human-dimension research on HABs to better understand how they shape coastal livelihoods and to develop more appropriate and effective policies and governance responses (Bauer et al., 2010; Sagarminaga et al., 2023; McKinley et al., 2024). Social science research helps to understand societal attitudes and perceptions of HABs, their key impacts on the blue economy, and the co-development of ideas for adaptation pathways that are more effective, socially accepted, and robust, particularly in contexts where little information is available (Bennett, 2016; Ward et al., 2022). Engaging stakeholder perceptions directly helps to envision adaptation pathways that are adjusted to local realities and are more responsive to societal needs (Ward et al., 2022).

We present the first study to use fuzzy cognitive mapping – a participatory modeling tool – to map harmful algal bloom drivers, impacts, and adaptation across different coastal user groups in Peru. We ask: (1) how different stakeholders understand the drivers and impacts of HABs, (2) which adaptation strategies they identify, and (3) whether adaptive capacity differs between actors. We focus on two coastal bays that are important sites for mariculture, a climate-vulnerable blue-economy sector in Latin America, to advance understanding of adaptation under climate change (Ekstrom et al., 2015; Galappaththi et al., 2020). The study also demonstrates that fuzzy cognitive mapping is a practical participatory method for capturing institutional dynamics and broader social-ecological complexity (Makris et al., 2024), thereby helping diversify the methodological toolbox for studying the human dimensions of HABs (McKinley et al., 2024). By addressing these questions, this article identifies the main livelihood impacts of HABs in two Peruvian bays, outlines key adaptation strategies, and shows how

HABs' impacts intersect with unequal adaptive capacities between small-scale producers and larger firms. In doing so, it offers insights into the social and governance dimensions of HABs, the uneven distribution of impacts and adaptive capacity, and the need for more just and responsive HAB governance.

2 Materials and methods

2.1 Study context

The study focused on HABs in Sechura and Paracas Bay, Peru. Sechura Bay is located in the northern province of Piura, while Paracas Bay lies in the central Peruvian region of Ica (Figure 1). Both bays are influenced by the Humboldt Current Upwelling System, which is one of the most productive marine ecosystems worldwide, driven by the upwelling of cold, nutrient-rich waters to the surface layer (Chavez et al., 2008). They host a large nearshore small-scale fisheries (SSF) sector that supports local livelihoods and food security, as well as scallop (*Argopecten purpuratus*) mariculture at depths of 5–30 m (Wolff et al., 2007; Mendo et al., 2016; Romagnoni et al., 2022). Nearshore fisheries and mariculture are particularly vulnerable to HABs, as research from other contexts shows (Díaz et al., 2019; Brown et al., 2020; Alvarez et al., 2024). Geographic features such as semi-enclosed bays, hosting many human activities (industry, fishing, processing), and lying near river mouths with intensive agriculture, potentially shape local HABs dynamics.

Paracas, meanwhile, historically played a significant role in scallop production before production shifted to Sechura in the early 2000s due to better seed supply, mismanagement in Paracas, and ecological conditions (Kluger et al., 2019b). Sechura is now Peru's leading aquaculture site, accounting for 83% of national scallop production and 50% of Latin America's as of 2013 (Kluger et al., 2019b; Mendo and Quevedo, 2020) and has helped place Peru among the world's top three scallop producers (FAO, 2025). In Sechura, the sector is estimated to employ around 25–000 workers in direct and indirect jobs as crews, in diving, processing plants, logistics, and other associated services (Kluger et al., 2019a). While scallops were historically managed under an open-access regime with many small producers and few regulations, production standards, and other socio-economic and institutional factors have driven privatization and concentration in resource ownership, with larger companies increasingly controlling processing plants and production licenses, and private investors now holding most scallop concessions in the bay (Schlüter et al., 2021, 2023).

Although both bays are primarily influenced by the upwelling system, their internal oceanographic conditions are highly dynamic, driven by forcing at multiple temporal scales, including daily variations in wind patterns and circulation, as well as the occurrence of El Niño/La Niña events. This variability increases the exposure of scallop cultivation (mainly practiced in the form of bottom culture) to environmental fluctuations, making it particularly vulnerable to natural shocks (Cueto-Vega et al., 2022; Kluger et al., 2022). Regular mortality events of scallops have been reported, explained by factors such as HABs, marine heatwaves, anoxia, and sulfuric plumes (Cueto-Vega et al., 2022). The El Niño Southern Oscillation (ENSO), a climate-oceanic phenomenon that causes extreme climatic variation, strongly influences the bays (Romagnoni et al., 2022). During the warm El Niño phase, sea surface temperature and precipitation increase, altering the dynamics of marine species and making certain HABs more likely (Sánchez et al., 2022; Cuellar-Martinez et al., 2023). These effects were felt during the localized Coastal El Niño in 2017 that heavily affected the SSF sector and paralyzed scallop production for more than a year (Kluger et al., 2019a; Kriegl et al., 2021, 2022). Currently, 85% of the scallop production is exported, with Europe and the US

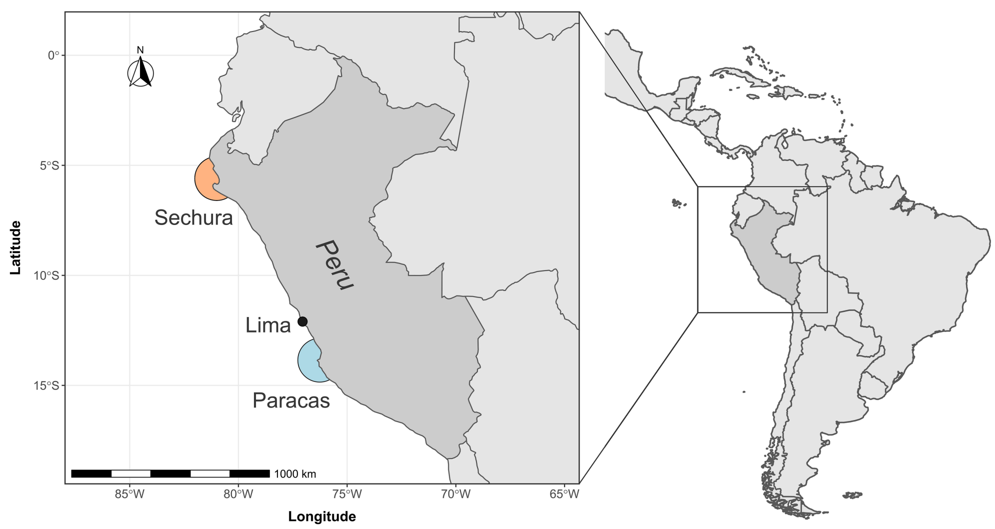

FIGURE 1
Map showing the location of the study regions, Sechura Bay and Paracas Bay, and the city of Lima, along the coast of Peru. The map was constructed within the R environment (R Core Team, 2025) using the rnaturalearth package (Massicotte and South, 2025).

being the most lucrative markets (Mendo and Quevedo, 2020; Kluger et al., 2022). This puts pressure on producers to comply with international and national sanitary standards, which creates risks given the occurrence of potentially toxic algal species (Cuellar-Martinez et al., 2023). Even though studies have identified traces of toxins that can cause paralytic shellfish poisoning (PSP), amnesic shellfish poisoning (ASP), and diarrhetic shellfish poisoning (DSP) in bivalves, fur seals, and sea lions, no case of human poisoning has been officially recorded in Peru (Mafra et al., 2023). Nevertheless, the national agency for fisheries health (SANIPES) can issue temporary harvest closures based on its toxin monitoring program when potential risks exist (Garteizgogeascoa et al., 2020a). The evidence that potentially toxic species are present in coastal Peru has been growing. Researchers have identified genus such as Alexandrium, Azadinium, Pseudo-nitzschia, Dinophysis, Fibrocapsa, and Prorocentrum (Sanchez et al., 2017; Cuellar-Martinez et al., 2021, 2023; Mafra et al., 2023; Tenorio et al., 2026).

While Paracas and Sechura share a history of scallop production and dependence on artisanal and industrial fishing, there are key differences. Sechura is the largest bay in Peru, with a population of around 94 207, whereas Paracas is one of the smaller bays and has a population of 10 082 (INEI, 2022). Paracas has become Peru's third most-visited tourist region, attracting 3.5 million visitors annually, while tourism plays a minor role in Sechura (Garteizgogeascoa et al., 2020b). Tourists are attracted by Peru's oldest coastal protected area, the Paracas National Reserve (PNR), established in 1975 and spanning over several bays (Damonte et al., 2026). Despite its protected status and state regulations, production of scallops, fishing, and kelp farming in Paracas continues as a hybrid arrangement of formal and informal extractive activities within or in the vicinity of the reserve (Damonte et al., 2026). Additionally, the towns north of Paracas host large fish processing plants, primarily producing canned fish, fish oil, and fishmeal. Pollution from local fish processing plants led to eutrophication and HABs in the bay, causing substantial economic losses, with revenue loss of $27.5 million for the anchovy industry and $1 million for mariculture (Kahru et al., 2004). Despite the differences, both places remain strongly connected, as many scallop company owners in Sechura originally came from the South and continue to move between the two as production conditions change.

2.2 Study design

Using fuzzy cognitive mapping (FCM) in focus groups, we analyzed coastal resource users' perceptions of the key drivers and impacts of HABs, the most important adaptation strategies, and the interactions between drivers, impacts, and adaptation. FCM is a participatory modeling tool increasingly applied in social-ecological systems research and in assessments of adaptive capacity to environmental change (Reckien, 2014; Furman et al., 2021). In FCM, stakeholders construct a concept map to externalize and formalize perceived causal relationships, creating a shared representation of a system of interest (Voinov et al., 2018). Participants identify relevant variables and connect them with causal arrows (Jetter and Kok, 2014). These can include ecological and biophysical factors as well as non-material factors such as norms, institutions, social practices, and governance arrangements. For each link, participants assign direction and indicate a strength using either categorical descriptors or semi-quantitative weights grounded in fuzzy logic (Kosko, 1986; Voinov et al., 2018). The resulting maps represent stakeholders' mental models of the system, and their normative views of how the system ought to work. The focus group discussions provide qualitative detail on how participants defined concepts and justified linkages. The resulting maps can be explored structurally to examine similarities and differences in perceptions across individuals and groups using network metrics (Özesmi and Özesmi, 2004). Additionally, "what-if" scenarios can be explored by modifying selected factors or introducing external interventions in the map and examining their relative effects on other factors in the system (Özesmi and Özesmi, 2004). Broader methodological guidance and reflections on challenges and opportunities in FCM are available elsewhere (Özesmi and Özesmi, 2004; Gray et al., 2014; Jetter and Kok, 2014; Makris et al., 2024). For this study, we followed the traceability procedure proposed by Olazabal et al. (2018).

Mapping was conducted in 17 in-person focus groups (typically 2–5 participants) with 48 participants in total during two months of fieldwork in Paracas Bay, Sechura Bay, and Lima in late 2022, of which one mapping was excluded because the discussion did not focus sufficiently on the central concept of HABs. Moreover, we conducted 6 semi-structured interviews for additional insights. Participants were recruited through purposive sampling based on contacts from the Humboldt-Tipping project[1] and then through snowball sampling. Participants included mariculture producers (small and large), scallop divers, fishers, producer associations, local municipality staff, researchers, and staff from the fisheries health agency (SANIPES) and the Institute of the Sea of Peru (IMARPE), as well as people working in tourism. Nevertheless, stakeholder categorization is fluid. For instance, actors were working both in tourism and mariculture, or local authorities also qualified as scientists. We distinguish larger and smaller mariculture producers even though that distinction is difficult to draw. Yet, previous literature suggests that production modes differ, as larger actors typically control more value-chain steps (harvest, processing, export), operate as formal companies, and hold larger scallop concessions (Schlüter et al., 2021; Kluger et al., 2022). Meanwhile, smaller mariculture producers have smaller concessions and do not control several steps of the chain. We opted for group mapping rather than individual mapping because it is time- and resource-efficient and yields a map that already reflects a degree of within-group deliberation and consensus (Jetter and Kok, 2014; Nyumba et al., 2018). Maps were developed using an open-ended procedure: Participants brainstormed concepts and drew links freely. After an introduction to FCM, participants described their understanding of HABs and then sequentially mapped perceived drivers, impacts, and adaptation strategies. Finally, groups discussed which adaptation strategies appeared most promising and what constraints shaped their feasibility and effectiveness. Participants assigned the sign and strength of each causal connection in a semi-quantitative manner using (+, ++, +++) for positive relationships or (-, –, -–) for negative relationships. Figure 2 presents an example of one FCM

1 https://humboldt-tipping.org/stakeholder

developed during the workshops, illustrating how participants represented perceived drivers, impacts, adaptation strategies, and causal relationships.

Following fieldwork, we analyzed workshop material to understand participants' perceptions of system components. Definitions and explanations of map concepts were extracted from audio recordings and compiled in a codebook (Supplementary Material). Before quantitative aggregation, maps were cleaned by harmonizing concept names, standardizing directionality, merging closely related variables, and removing concepts that lay outside the system boundaries or were purely definitional (Jetter and Kok, 2014; Olazabal et al., 2018). Cleaned maps were converted into adjacency matrices, i.e., square matrices listing concepts on both axes, in which the presence and weight of relationships between concepts are recorded in the corresponding cells (Özesmi and Özesmi, 2004). Matrices were aggregated by stakeholder group (scientists, local authorities, small- and large-scale mariculture, and fishing), and an overall crowd map was created by summing individual matrices and dividing by the number of maps in each group. This aggregation method gives greater prominence to relationships that recur across maps (Aminpour et al., 2020). We combined maps into a crowd model because our primary objective was to capture the most salient shared perceptions of HABs dynamics among coastal-resource users in Peru. As both studied bays share many features, including nearshore fisheries, mariculture activities, and HAB-related pressures, aggregation offers a synthesis of shared stakeholder knowledge and common social-ecological dynamics, while recognizing local variation, which is discussed below. As such, the crowd model serves as a synthesis of shared stakeholder knowledge across two cases in coastal Peru and may provide a more robust representation of perceived system dynamics than models derived from narrower groups (Aminpour et al., 2020) or a single site.

We used Mental Modeler software to examine the maps' structure, including centrality, outdegree, and indegree. Outdegree captures the strength of causal links leaving a concept, indegree the strength of links entering a concept, while centrality is the sum of indegree and outdegree (Singh and Chudasama, 2017). Outdegree helped identify concepts exerting a strong influence on the system, including key drivers and adaptation strategies, while centrality helped identify highly connected HABs' impacts. Finally, we used the Mental Modeler what-if scenario tool on the crowd map to explore system responses to a simulated increase in HABs and to examine the simulated effects of adaptation strategies and institutional responses. In these simulations, concepts are assigned to activation values (1 = full activation; 0 = no activation), with their impact then propagating through the map by multiplying the activation vector with the connection matrix. Importantly, this procedure represents perceived system behavior and feedback and is not a statistical forecast (Singh and Chudasama, 2017).

To examine the perceived effects of increased HABs intensity on the system, we ran a simulation in which the HABs component was simulated to increase to a maximum value of 1. This type of analysis is commonly used in FCM studies to explore perceived variation in system outcomes under extreme conditions (Henly-Shepard et al., 2015; Furman et al., 2021). The resulting system state was then compared with the steady-state model without any simulated change (Gray et al., 2015). This comparison shows how an increase in HABs may influence system components, directly or indirectly, through the dynamics defined in the crowd model. Here, we focus on the relative change in those components that were classified as HABs' impacts. We then focused on scenario analysis of proposed adaptation strategies in the mariculture sector. We analyzed mariculture specifically because it emerged in focus group discussions and network statistics as the sector perceived to be most affected by HABs. We compared three sets of adaptation strategies in the context of HABs: (1) those already practiced by small-scale mariculture producers, (2) those already practiced by large-scale mariculture producers, and (3) a combined set of current and

FIGURE 2
Fuzzy cognitive map created by mariculture producers in Sechura. Drivers of harmful algal blooms are shown in yellow, impacts in pink, and adaptation strategies in orange. Adapted from Makris (2023).

hypothetical strategies. These scenarios were inductively derived from the focus groups, where adaptation differences between small-scale, large-scale, and hypothetical adaptation emerged as key distinctions. Building on the previous simulated increase of HABs, we then compared these three adaptation scenarios by activating the concepts associated with each set to a medium activation level (0.4). The comparison focused on the extent to which these strategy sets mitigated the key HAB-related impacts. A limitation is that the scenarios could not be validated with participants in a follow-up workshop due to time and resource constraints.

3 Results

3.1 Key drivers, impacts and adaptation strategies identified through the crowd model

The aggregated crowd map that combined all individual maps contained 113 variables (Figure 3). Of these, 29 variables were HABs drivers, 37 variables related to impacts, and 36 variables described adaptation strategies and barriers. Overall, the graph contained 293 connections, averaging 2.6 connections per component (Table 1). The most frequently mentioned concepts were Mortality Scallops & Other Benthos and Anoxia/Hypoxia (94% of maps), followed by Sea Surface Temperature (82%), Mortality Fish (82%), Debts (76%), Stranding (76%), Discoloration (65%), Income (65%), and Toxins (65%).

3.2 Drivers

Outdegree scores identified the drivers of HABs perceived as most influential across the system: Sea Surface Temperature (0.80), Contamination (0.70), Local Wind Patterns (0.50), Nutrients (0.40), River Runoff (0.39), Summer Season (0.33), Semi-Closed Bay (0.27), Local Currents (0.25), Warm Ocean Current (0.25), and Northern Winds (0.25). Participants agreed that HABs occur regularly, but only cause major impacts when blooms persist for several days. These events were associated with the convergence of multiple factors, typically occurring during the Summer Season (December-April), when Warm Ocean Currents dominate, particularly in El Niño years. HABs occurrence was linked to changes in Sea Surface Temperature and Reduced Water Renewal, associated with weaker Local Winds, strong Northern Winds, and certain current dynamics. The semi-closed bay morphology and potential nutrient loads or contamination – linked to human settlements, fishing and mariculture waste, river runoff, ballast water, and local mining – were also perceived to increase bloom likelihood and intensity, although most stakeholders did not rank these as primary drivers.

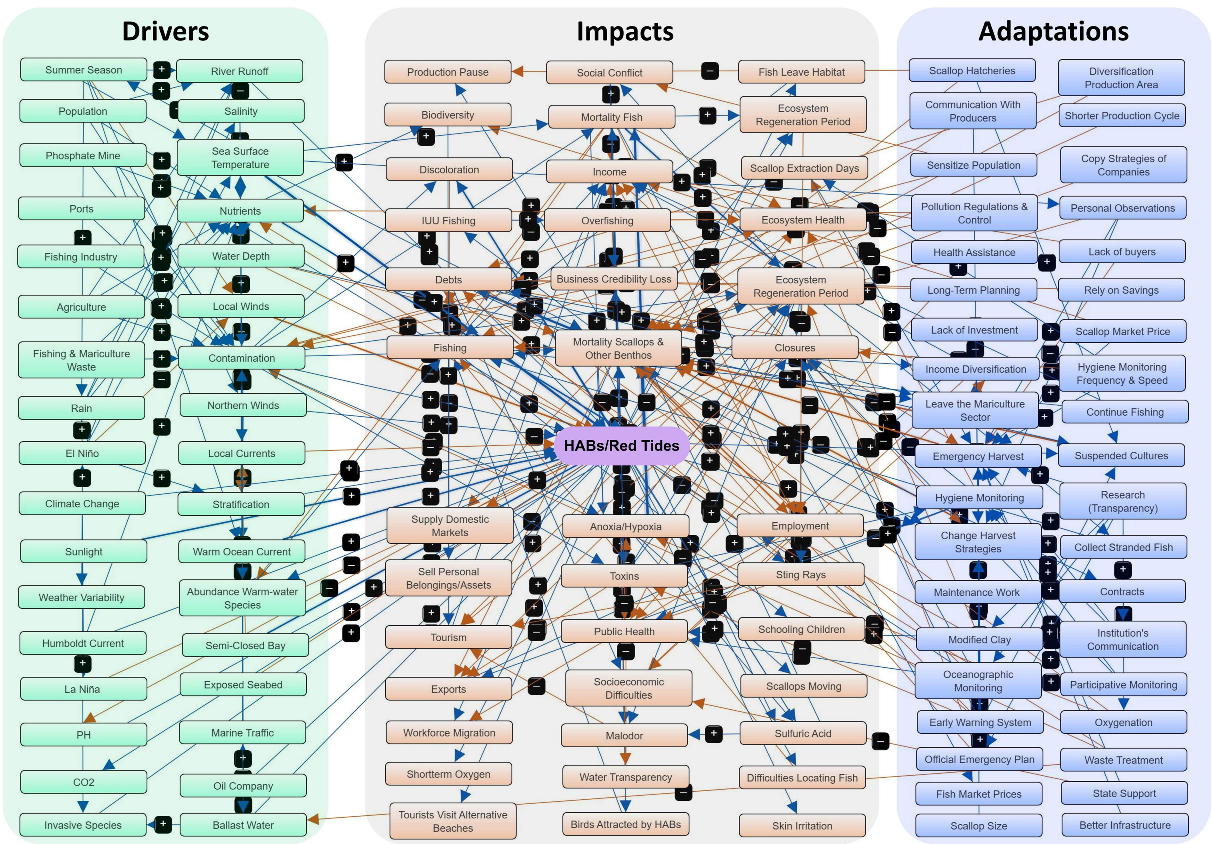

FIGURE 3
Aggregated crowd model of all focus group discussions. Drivers of harmful algal blooms are in green, impacts in orange, and adaptation strategies and barriers to adaptation in blue.

TABLE 1 Network statistics of the crowd model and each stakeholder group model: transmitter variables have only outgoing links, receiver variables only incoming links, and ordinary variables both.

Stakeholder group	Crowd map	Authorities	Small-scale mariculture	Large-scale mariculture	Fisheries	Scientists
Maps (N)	16	2	6	1	3	5
Number of Variables	113	42	78	33	35	59
Number of Transmitter	34	16	30	13	4	21
Number of Receivers	19	9	13	10	11	9
Number of Ordinary	60	17	35	10	20	29
Number of Connections	293	50	147	34	49	119
Mean No. connection/ variable	2.6	1.19	1.88	1.03	1.4	2.01
Complexity	0.55	0.56	0.43	0.77	2.75	0.42
Density	0.02	0.03	0.02	0.03	0.04	0.03
Driver Variables (%)	29	29	29	28	24	38
Impact Variables (%)	37	41	34	38	59	33
Adaptation Variables (%)	34	29	38	34	18	29

Complexity is the receiver-to-transmitter ratio, and density measures overall map connectivity (Özesmi and Özesmi, 2004; Gray et al., 2014).

3.3 Impacts

Simulating HABs at the maximum activation level (1) produced perceived increases in Anoxia/Hypoxia, Mortality Scallops & Other Benthos, Mortality Fish, Debts, Toxins, Discoloration, Stranding of Marine Organisms, Bad Smell, Closures, and reductions in Employment, Income, Ecosystem Health, Tourism, Public Health, and Fishing (Figure 4). These results, combined with the focus group discussions, identified four sectors as affected by HABs: scallop mariculture, fishing, tourism, and public health. The focus groups further provided more detailed insight into the specific impacts within each sector.

Participants agreed that scallop mariculture is the sector most affected by HABs, while impacts on fishing, public health, and tourism were seen as comparatively minor. Toxins played a smaller role than anoxia/hypoxia in participant accounts. The main perceived relevance of toxins was the need for monitoring and hygiene control, while also being a potential risk for public health and marine life. Yet, participants reported that toxin levels exceeding regulatory thresholds are not common. When thresholds are exceeded, scallop harvesting stops until concentrations decline, usually leading to short closures. Although exceedances have occurred, no official human intoxication has yet been reported in coastal Peru. Nevertheless, scallop divers mentioned skin irritations during HABs events, and participants noted weak coordination between the sanitary control agency and the health sector, along with limited toxin awareness among health officials and the wider population, suggesting that intoxication may go unreported or not be linked to HABs. Toxins were also seen as a future risk to undermine exports and induce long-term closures conditioned by hygiene regulations.

Participants emphasized that HABs occur regularly and that anoxia across mariculture zones is a major impact. Scallop mortality caused by anoxia was often described as spatially patchy: while certain areas are affected, others are not. This created divergent impact perceptions across producers, depending on the production zone. However, participants also described periodic bay-wide mortality events every few years. In Sechura, producers reported that red tides contributed to over 80% of production losses in 2012, 2016, 2017, and 2019. Indirect impacts included increased debt, lower income, and reduced employment, mainly linked to mortality events and the costs of monitoring and closures. These socio-economic effects were described as more impactful than in small-scale fisheries because scallop farming requires higher investment and scallops are particularly vulnerable. Production cycles last 7–18 months, usually around 9, during which producers invest in scallop seeds, fuel, labor, logistics, and monitoring. If a HABs destroys production, both product and investment are lost while fixed maintenance costs remain. This is especially severe when mortality events occur in summer, once scallops have reached commercial size. Producers then need substantial capital to restart; some smaller producers described selling assets (televisions, cars, even houses) to repay creditors and finance new investment. Large-scale producers were also affected since consecutive mortality years can threaten business survival. Participants also highlighted a lack of labor security, negative secondary economic effects on sectors linked to mariculture, and migration in search of work after HABs-induced mortality events.

Fish were generally described as less affected by HABs than scallops. Offshore stocks such as anchovies and industrial fleets operating away from the coast were considered largely unaffected. Participants nevertheless described occasional cases in which fish shoals became trapped between the shoreline and algal patches and suffocated as oxygen levels dropped. Dead fish stranded on beaches and decomposing marine life were also said to further accelerate oxygen depletion and pose a health risk. Although fish mortality and stranding emerged as central impacts in the crowd model, participants described them as having fewer secondary socio-economic effects than scallop mortality. Nearshore artisanal raft fishers (pinteros) reported that discolored water patches (aguaje)

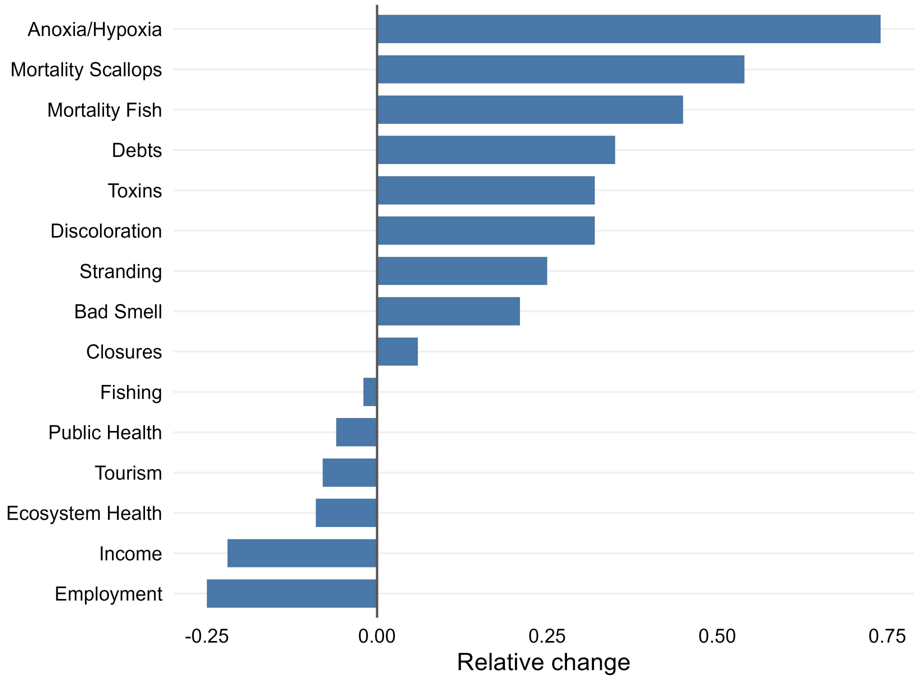

FIGURE 4
Scenario outputs from the crowd model after simulating an increase in harmful algal blooms to its maximum value of 1. Each bar represents the relative change in systems components classified as harmful algal bloom impacts. Adapted from Makris (2023).

coincided with shifts in fish distribution and made fishing more difficult by reducing visibility, complicating fish detection, and sometimes causing mortality. White discoloration in particular were said to temporarily reduce catches, although participants could not determine whether these patches reflected algal blooms or other oceanographic conditions. The main indirect impact for small-scale fishers related to spillover effects from the scallop sector: after major scallop mortality events, increased fishing pressure was observed as scallop workers turned to fishing, often with limited skills and a greater likelihood of using harmful gear or engaging in IUU fishing.

Tourism was frequently mentioned as potentially affected by HABs, but perceived impacts were generally minor, especially in Sechura, where tourism is limited. Discoloration and the smell of decomposing algae or stranded fish can deter visitors, but such events were described as rare. In Paracas, milky water discoloration was sometimes even perceived positively because tourists associated it with a "Caribbean water color," although it was unclear whether this was caused by HABs. The main tourism-related impact described in Paracas was sting ray proliferation, with rays perceived to move closer to shore during HABs events and injure tourists and fishers. Overall, because beach and swimming tourism are uncommon, most tourists were not seen as directly affected by blooms.

3.4 Adaptation strategies and pathways

The aggregated maps included 36 adaptation-related concepts, including strategies, limiting factors, and enabling conditions. Outdegree scores identified Early Warning Systems as the most influential strategy, while not being actually practiced (0.54). Among practiced strategies, Hygiene Monitoring (0.39), Emergency Harvests (0.33), Income Diversification (0.31), Changes in Harvest Strategies (0.31), and Suspended Cultures (0.29) were perceived as having the greatest influence on the wider system (Table 2).

To probe differences between large-scale (LSM) and small-scale mariculture (SSM), scenario simulations compared adaptation pathways and their perceived ability to mitigate HABs mariculture impacts (Scallop Mortality, Debts, Employment, and Income) (Figure 5). Overall, adaptation measures were generally perceived to reduce impacts to some extent, but large-scale mariculture strategies were considered more effective than those available to smaller producers. Hypothetical strategies were perceived to offer the largest potential reductions.

Outdegree scores and focus group discussions indicated that two current adaptations are key, both among small- and larger mariculture producers (Table 2): Changes in Harvest Strategies and Emergency Harvests. Emergency harvests refer to last-minute extraction when HABs are likely. Changes in harvest strategies refer to harvesting earlier (November-January) to reduce exposure during the warm-water season. Participants highlighted incentives to leave scallops longer in the water, including potentially faster summer growth and reduced supply coupled with higher demand later in the season (higher prices). Producers, therefore, play with the probability of natural risks and make decisions on harvesting based on the information they have. Larger companies use real-time satellite data and maintain direct communication with researchers and other companies in the wider area, giving them an informational advantage to make decisions under environmental uncertainty. In contrast, some SSM producers criticized their relationship with IMARPE and SANIPES and their limited access to research and technical solutions. Late official warnings on HABs and El Niño

TABLE 2 Ranking of adaptation-related concepts based on outdegree scores in the crowd map.

Adaptation strategies	Outdegree score	Practiced, hypothetical, or limiting factor	Practiced by which stakeholder
Early Warning System	0.54	Hypothetical	
Hygiene Monitoring	0.39	Practiced	Local Scientists
Emergency Harvest	0.33	Practiced	Small-scale mariculture (SSM) & Large-scale mariculture (LSM)
Income Diversification	0.31	Partly Practiced	SSM & LSM
Change Harvest Strategies	0.31	Practiced	SSM & LSM; advantages LSM
Suspended Cultures	0.29	Partly Practiced	LSM
Research (Transparency)	0.25	Partly Practiced	Local Scientists and Authorities: advantages of LSM
Oceanographic Monitoring	0.25	Partly Practiced	All; advantages of LSM
Official Emergency Plan	0.18	Hypothetical	
Modified Clay	0.17	Hypothetical	
Diversification Production Area	0.16	Partly Practiced	LSM
Pollution Regulations & Control	0.14	Partly Practiced	Authorities
Waste Treatment	0.14	Hypothetical	
Improve Institution's Communication	0.14	Limiting Factor	
State Support	0.12	Hypothetical	
Lack of Buyers	0.12	Limiting Factor	
Communication With Companies and Fishers	0.1	Practiced	SSM & LSM
Participative Monitoring	0.1	Hypothetical	
Hygiene Monitoring Frequency & Speed	0.1	Limiting Factor	
Oxygenation	0.1	Partly Practiced	advantages LSM
Personal Observations/Predictions	0.1	Practiced	SSM, LSM
Scallop Market Price	0.08	Limiting Factor	
Scallop Size	0.08	Limiting Factor	
Scallop Hatcheries	0.08	Partly Practiced	LSM
Sensitize Population	0.08	Hypothetical	
Lack of Investment	0.06	Limiting Factor	
Better Infrastructure	0.06	Limiting Factor	
Scallop Extraction Days	0.04	Limiting Factor	
Long-Term Planning	0.04	Practiced	LSM
Continue Fishing	0.04	Practiced	Fisheries, SSM
Health Assistance	0.04	Hypothetical	
Copy Strategies of Companies	0.02	Practiced	SSM
Shorter Production Cycle	0.02	Partly Practiced	SSM
Collect Stranded Fish	0.02	Practiced	Coastal population
Rely On Your Savings	0.02	Partly Practiced	SSM

Concepts were classified as practiced strategies, hypothetical strategies, or limiting factors based on explanations provided during the focus group discussions.

events were repeatedly highlighted as contributing to chaotic emergency harvests. Thus, participants called for constant, transparent monitoring and an early warning system to support harvest and seeding decisions. Other strategies further differentiated LSM from SSM. Companies were described as diversifying production areas to spread risk across zones, while many smaller producers remain concentrated in fewer areas. Companies also invested in suspended cultures, allowing vertical movement during blooms by bringing scallops closer to the surface, where oxygen content is higher. Moving suspended cultures across zones was described as theoretically possible but not practiced in Sechura due to heavy weights and major HABs events in 2012 and 2017, thus still causing complete losses for larger companies. Finally, companies are more likely to operate (and collaborate with) scallop hatcheries, reducing

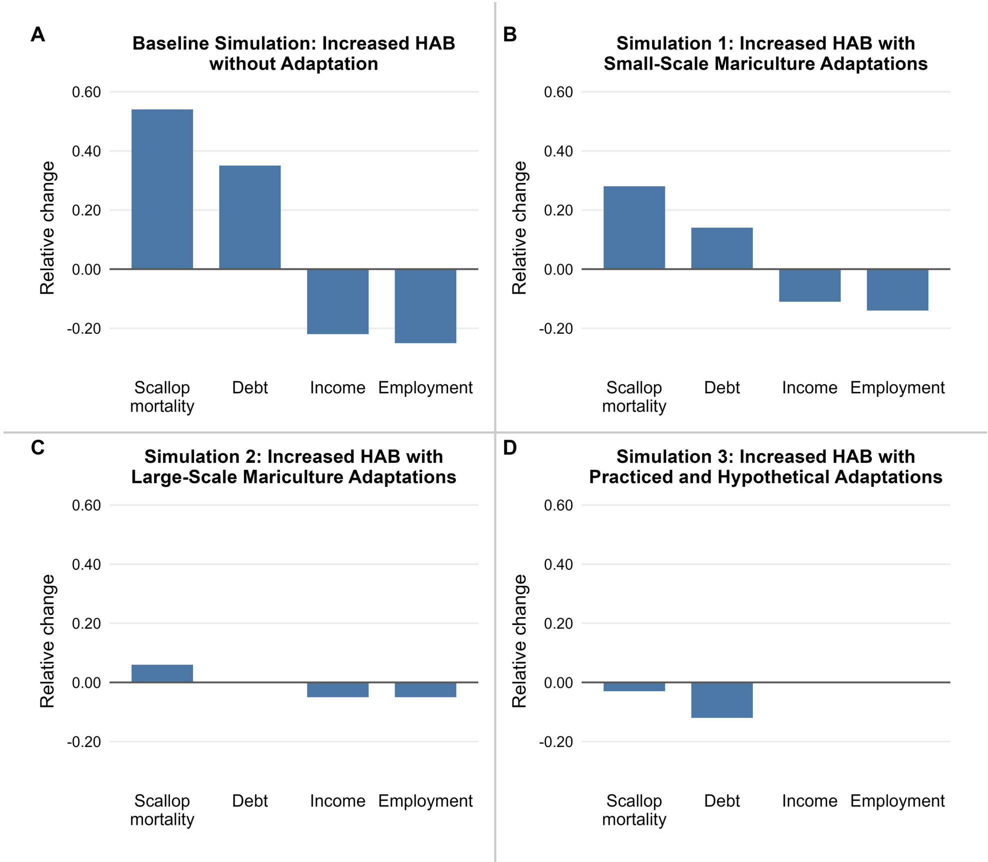

FIGURE 5
Scenario analysis of adaptation strategies in the mariculture sector (crowd model). The initial simulation shows the perceived changes in mariculture-related impacts after the HABs concept was set to its maximum value **(A)**, relative to the steady-state model without simulated change. Simulations **(B–D)**, then assess the extent to which modest increases (0.4) in three sets of adaptation strategies mitigate selected HAB-related impacts under increased HABs conditions. Set B includes strategies practiced by small-scale mariculture producers (SSM), Set C strategies practiced by large-scale mariculture producers (LSM), and Set D, a combined set of all currently practiced and hypothetical strategies identified by participants. Adapted from Makris (2023).

reliance on natural banks and enabling faster restarting after mortality events. SSM producers described constraints, especially for emergency harvests, for instance, logistical bottlenecks at landing sites and dependence on company-controlled processing facilities for cooling and processing. This dependence enables companies to influence prices and reject products not meeting size or quality standards or simply prioritize their own product. SANIPES monitoring was another constraint – given that the product can only be extracted once the monitoring results have arrived, which at times is delayed and can thus complicate emergency harvests. SSM producers reported losing harvests while waiting and demanded faster emergency procedures and an official extraction plan. Companies were described as having the opportunity to harvest while monitoring results are pending by holding scallops in “quarantine” cold storage until checks are completed. Finally, the ability to cope with socio-economic impacts also differed. Companies were described as having better access to financial capital and planning production long-term (up to five years), incorporating expected losses into business planning and negotiating financing accordingly. SSM producers described struggling to access formal investment since banks stopped issuing loans for scallop production. Finally, income diversification was repeatedly framed as a key small-scale producer response (macroalgae, mussels, tourism in Paracas), though many producers struggle due to limited market access, demand, and investment. Participants emphasized that no state program currently supports the diversification activities of scallop producers.

3.5 Between-group perception differences

Some differences in the perception of the stakeholder groups could be observed during focus groups, especially regarding confusion over what defines HABs/red tides. Most participants described HABs as patches of microalgae associated with water discoloration and oxygen depletion. Fishers and producers used “red tide,” while scientists preferred the term “harmful algal blooms” and argued that color-based terms can be misleading (including alternative labels such as brown/black waters). “Aguaje” was used to describe diverse phenomena. For some, it was a synonym for HABs/red tides, for others, to describe warm-water currents or to refer to the mortality events. The most contested issue was the attribution of scallop and fish mortality. In Sechura, stakeholders generally viewed HABs and other natural phenomena as central drivers of mass mortality, with disagreement focusing on the role of the local phosphate industry.

In Paracas, anthropogenic contamination was considered more central, and perceptions diverged strongly: local scientists argued mortality is primarily driven by natural dynamics such as HABs, while SSM and small-scale fishers attributed mortality to waste disposal by local fishmeal factories. This difference also appeared in map structure: Sea Surface Temperature had the highest outdegree in Sechura (1.2), while Contamination dominated in Paracas (1.7).

4 Discussion

First, we discuss how stakeholders make sense of HABs and related marine mortality events under conditions of uncertainty, highlighting areas of knowledge convergence and disagreement in terminology, impact attribution, and governance responses (Section 4.1). Second, we examine how perceived impacts differ from the risks most directly addressed by current HAB governance (Section 4.2). Third, we discuss the adaptation strategies identified by participants and show how unequal access to information, infrastructure, finance, and institutional support shapes adaptive capacity across different actors (Section 4.3).

4.1 Converging and diverging understandings of HABs, their drivers and impact attribution

The results show both convergence and divergence in how stakeholders understand HABs, their drivers, and related marine mortality events. Knowledge of HAB drivers and key impacts was generally high among both scientific actors and local resource users, highlighting the latter's ecological knowledge and their practice of reading environmental signals and adjusting their behavior accordingly (Davis and Wagner, 2003). For instance, fishers and mariculture producers interpreted HABs events and the associated water discoloration as indicators of ecosystem change and responded by altering fishing practices or adjusting the timing of scallop harvest, patterns also reported in other studies on HABs perceptions in Ecuador (Borbor-Córdova et al., 2018). However, our results also indicated that this understanding remains concentrated in a core group of mariculture producers, scientists, and local ocean authorities. Beyond these actors, awareness of HABs was limited, even among municipal and health authorities. This finding resonates with calls from other case studies to raise awareness among a broader set of stakeholders – including public health, tourism, and the wider population (Borbor-Córdova et al., 2018; Brown et al., 2020; Mafra et al., 2023).

Moreover, disagreements persisted over the definition of HABs, the attribution of mortality events, and certain governance responses. This reflects the difficulty of attributing fish and scallop mortality even in scientific research, given the complexity of marine ecosystems and the range of interacting variables involved (Brown et al., 2020). In practice, stakeholders used terms such as "marea roja" and "floraciones algales nocivas", "aguaje", "brown tide", and "white waters", to refer to distinct or overlapping marine disturbances, including marine heatwaves, sulfur plumes, and contamination-induced changes (Cueto-Vega et al., 2022; Cueto-Vega et al., 2024; Rioual et al., 2025). This complexity highlights the need for clearer classification and communication of these phenomena to improve how stakeholders interpret and respond to marine mortality events (Table 3; Figure 6).

This ambiguity also has political significance because it shapes how the causes of scallop and fisheries mortality are understood. In Paracas, for instance, small-scale mariculture producers and fishers often considered contamination from fishmeal factories a central cause of marine anomalies, whereas local authorities emphasized the natural character of HABs. This disagreement remains shaped by memories of the major bloom in the early 2000s, which caused significant economic losses, port closures, social unrest, and severe impacts on aquaculture and fishmeal production (Kahru et al., 2004). Although effluent pipelines were later installed, local doubts persist, reinforced by earlier findings that fishery effluents can interact with HABs to trigger benthic mortality (Cabello et al., 2002). How actors frame HABs – whether as natural events, pollution-driven phenomena, or a combination of both – plays a crucial political role in determining who is seen as responsible for bearing the costs and in shaping which solutions are considered legitimate and by whom. In Paracas, this is closely tied to longstanding conflicts over fishmeal effluents and institutional responsibilities, whereas in Sechura, it relates more to how different

TABLE 3 Definitions of seawater discoloration phenomena and associated local terminology in Peru.

Terms	Definition
Algal blooms (floraciones algales)	Increase in the abundance of microalgae and cyanobacteria, which may or may not change seawater color; usually caused by harmless species, with no direct harmful effects.
Harmful algal blooms (floraciones algales nocivas)	Blooms caused by harmful microalgae or cyanobacteria, including toxin-producing species. HABs can harm humans, marine organisms, or ecosystems. They do not necessarily involve high biomass or visible seawater discoloration. However, some harmful effects, such as hypoxia or anoxia, are biomass-dependent; in such cases, even normally non-harmful species may become harmful when they reach exceptionally high biomass (Smayda, 1997; Anderson et al., 2002)
Red tide (marea roja),brown tides (marea marrón/ chocolate)aguaje, aguaje rojo	Terms used by local people to describe changes in seawater color associated with algal blooms and Harmful algal blooms.
White/turquoise/milky waters (aguas blancas/ lechosas)sulfur plumes (evento sulfuroso)aguaje blanco	Phenomena not caused by algal blooms. They are associated with sulfides in the water column, including toxic H^2S, which can give the water a milky turquoise discoloration (Rioual et al., 2025).

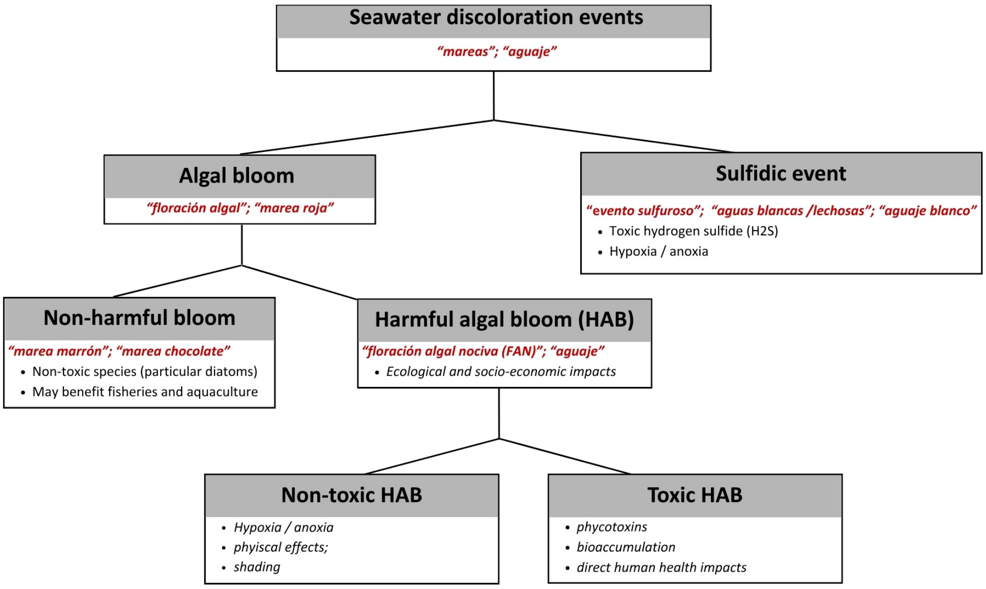

FIGURE 6
Defining and contrasting local and scientific terminology for seawater discoloration and related phenomena in Peru. Local terms are shown in red and set in quotation marks. "Aguaje" is an ambiguous term used to describe seawater discoloration events of diverse origin. Depending on the local context, it may refer to algal blooms, sulfur-related white-water events associated with the presence of toxic H^2S, or even contamination-related episodes.Tables.

institutions share responsibility for HABs monitoring and response, and to whether certain adaptation measures, such as experimental interventions, such as modified clays, are considered desirable.

The political character of HABs in Paracas and the contestation around their management also resonates with other Latin American case studies. In Chiloé, Chile, a major HAB crisis likewise produced competing narratives, with some fishers, NGOs, and Indigenous communities challenging official accounts that framed the crisis primarily as a natural event and downplayed the role of the salmon industry (Mascareño et al., 2018; Arriagada et al., 2025). As in Paracas, these disputes were not only about causality, but also about responsibility, trust, and the legitimacy of crisis responses. Our findings from Paracas and Sechura, while less pronounced, echo these dynamics. More broadly, this suggests that the attribution of marine life mortality is deeply political, and that HABs, marea roja, or aguaje can function as boundary objects: flexible labels that are mobilized differently depending on actors' interests and positions (Star and Griesemer, 1989; Cohen, 2012). This also points to the importance of institutional trust. HABs governance in these settings should therefore be understood not as a standalone technical management problem, but as part of longer-running environmental conflicts over causes, impacts, responsibility, and the institutional and social relations through which these are negotiated. As shown in Chiloé and reflected in our Peruvian cases, high uncertainty over causes, responsibilities, and adaptation pathways can deepen institutional distrust and constrain adaptation and livelihood diversification (Arriagada et al., 2025). In this context, clearer communication, including more precise differentiation between the various marine disturbances discussed here (Table 3; Figure 6), alongside more inclusive forms of environmental governance and participation, may help build trust and support more legitimate adaptation responses (Arriagada et al., 2025).

4.2 Perceived impacts and the scope of HAB governance

At the level of risk perception, stakeholders associated HABs with anoxia, hypoxia, mass mortality, and toxins, as well as certain ecosystem impacts. At the level of perceived impacts, however, they placed much greater emphasis on the economic and livelihood consequences of mortality events and ecosystem changes rather than on public health risks, the toxin-related costs, or tourism impacts. This is notable given the centrality of toxins in Peru's regulatory frameworks and scientific discourse, and the prominence of these other factors in studies from other contexts (Hoagland et al., 2002; Kouakou and Poder, 2019; Alvarez et al., 2024; Hamel et al., 2024). Instead, participants consistently framed HABs primarily in terms of anoxia or hypoxia, mass mortality, and their economic consequences: dead scallops and fish, lost harvests, debt, and employment loss. These concerns extended beyond producers themselves, as stakeholders also described wider ripple effects on transport, processing, gastronomy, logistics, and community well-being in coastal areas. Similar indirect socio-economic effects have also been documented in other HABs contexts (Van Dolah et al., 2016; Willis et al., 2018). Toxins mattered mainly because they triggered SANIPES closures and threatened access to export markets, rather than because stakeholders perceived major local health impacts. Taken together, these findings suggest that stakeholder risk perceptions and existing HABs governance are not fully aligned. Current monitoring and response regimes in export-oriented mariculture are strongly toxin-centric and market-facing, with institutional attention focused on seafood safety and regulatory compliance (Cuellar-Martinez et al., 2018; Mafra et al., 2023; Müller et al., 2020). By contrast, the mortality events, deoxygenation, and socio-economic disruptions that local actors perceive as most consequential receive less direct institutional attention. This matters not only in the Peruvian case: studies have also described the growing importance of oxygen depletion in the ocean, with hypoxic and anoxic coastal zones increasing globally (Diaz and Rosenberg, 2008). SANIPES has a clear mandate for food safety and toxin monitoring, and IMARPE provides scientific and technical support, but neither appears to have an explicit operational mandate to address the socio-economic consequences of large-scale mortality events. This points to an uneven governance landscape for HAB-related risks in Peru: toxin risks are comparatively well governed, while the broader livelihood and adaptation challenges associated with mortality events remain less clearly addressed.

4.3 Adaptation strategies and unequal adaptive capacity

While many adaptation strategies were mentioned, we found that the impacts of HABs were perceived to be unevenly distributed across coastal livelihoods and social groups. While impacts on the scallop sector were considered substantial overall, small-scale aquaculture operators were seen as more vulnerable than larger companies. Larger mariculture firms had more, though still imperfect, options to cope and adapt: they could diversify production areas, invest in suspended cultures, hatcheries, oxygenation-technology to mitigate anoxia, and infrastructure, and engage in longer-term planning and negotiated financing. They also benefited from information-related advantages, including access to satellite data, direct contact with researchers, and denser networks with other companies, which enabled them to interpret and respond to environmental signals more effectively. By contrast, small-scale mariculture producers were constrained to a smaller set of adaptation strategies. They relied on emergency harvests under logistical dependence on buyers and processors, attempting to imitate the strategies of larger companies without having comparable resources. Many producers fell back on savings, selling assets, and informal debt to cope with losses. In this context, social structures and relationships – for example, within families, neighborhoods, or producer organizations – play an important role in enabling or constraining these strategies in the face of environmental change (Kriegl et al., 2022). Infrastructure and market power asymmetries were also central: small-scale producers depended on company-controlled processing facilities and cold chains, companies could reject product and negotiate prices, and SANIPES sampling schedules favored large-scale producers, who could harvest into cold-storage quarantine, while small-scale producers lacked such options. Notably, the adaptation strategies receiving the most attention from authorities and scientific experts were predominantly technical – such as early warning systems, monitoring programs, and suspended cultures – whereas many affected producers emphasized the need for state support for livelihood diversification and for addressing the equity implications of adaptation.

These findings show that HABs impacts intersect with broader socio-economic transformations in the mariculture sector, including formalization, privatization, and the concentration of access rights in response to export-oriented demands such as food safety and legal changes in the sector (Schlüter et al., 2021; Kluger et al., 2022). On the ground, these processes affect smallholders who struggle with the costs of cold storage, certification, and monitoring, which in turn shape their ability to cope with environmental shocks such as HABs. After environmental shocks, some producers enter contractual relations with larger companies in order to remain in the sector, reinforcing a broader trend from more open access arrangements towards private property regimes and license concentration in fewer hands (Schlüter et al., 2023). In this context, previous work also suggests that better access to credit, insurance, and extension support could help mitigate the hardship faced by smaller producers (Schlüter et al., 2021, 2023). From this perspective, HABs adaptation is not only limited by awareness or the lack of technical options, but by unequal access to information, infrastructure, and capital along the value chain. The hazard may be natural and recurrent, but the disaster is socially mediated through the ways mariculture is financed and governed, and through the livelihood structures of Sechura and Paracas.

These findings connect to a growing literature on interacting stressors in coastal communities, such as blue growth, financialization, and area-based conservation, which can intensify existing vulnerabilities and erode adaptive capacity (Bennett et al., 2014; Knott and Neis, 2017; Barbesgaard, 2018). They also resonate with recent calls to pay greater attention to equity and justice in HAB governance. As HAB frequency and duration increase, distributional impacts are likely to become more pronounced, yet HAB research has so far paid limited attention to social justice, inclusivity, and equity (Jardine et al., 2020; McKinley et al., 2024). Our findings support calls for stakeholder mapping and closer analysis of how HAB events and related management measures shape distributional outcomes across affected areas (Jardine et al., 2020; McKinley et al., 2024). In Sechura, trends of resource concentration and grabbing (Schlüter et al., 2021) intersect with HAB shocks to create particularly difficult conditions for small-scale actors. Engaging more explicitly with the blue justice literature (Blythe et al., 2023) and adopting a stronger social-ecological and distributional lens on HABs can help move analysis beyond aggregate economic impact assessments. Such a lens can reveal who bears which costs, who can adapt, and under what conditions, while also identifying where interventions are most urgently needed to support more just adaptation pathways. Greater attention to equity in HAB decision-making may also improve social cohesion and reduce conflicts associated with HABs as environmental shocks (Hamel et al., 2026).

4.4 Governance implications

Bringing together system knowledge of diverse actors helped identify 36 adaptation strategies and provided practical insight into the current governance landscape of HABs in Peru. Across stakeholder groups, two priorities stood out: implementing an early warning system and strengthening existing monitoring schemes. Discussions also highlighted key barriers and institutional gaps, pointing to a need for real-time information, clear emergency protocols, higher monitoring frequency during summer months, reduced processing bottlenecks, and support for suspended culture and hatcheries. Because HABs cut across sectors, coordination should be formalized through an inter-institutional committee linking mariculture and fisheries (PRODUCE), public health (MINSA), tourism (MINCETUR), and environmental enforcement bodies and industries with significant environmental impacts (Makris and Kriegl, 2025). Public awareness and communication around HABs risks also need to be strengthened, particularly in the public health and tourism sectors and in relation to toxin exposure and the attribution of mortality events. Finally, our findings suggest that reducing asymmetries in adaptive capacity to environmental risks should be treated as an important objective not only for HABs governance, but also for scallop and fisheries governance more broadly. In Sechura, cooperative-oriented policies historically favored small-scale producers through formal access and production rights, but without complementary institutions for risk-sharing, financing, and HAB-related coping support, these protections were insufficient for many smaller producers and ultimately contributed to the concentration dynamics described above (Schlüter et al., 2023). In this regard, the insights from this study into asymmetries in adaptive capacity can help inform more effective and equitable governance responses.

5 Conclusion

Despite their social, economic, and political impacts, the human dimensions of HABs have been studied in only a few Latin American contexts (Borbor-Córdova et al., 2018; Mascareño et al., 2020; Hamel et al., 2026), and no prior study has drawn on the perspectives of diverse coastal actors to examine their dynamics in Peru. To address this gap, we used FCM with fishers, scallop producers, researchers, public authorities, and tourism officials to identify perceived drivers, impacts, and adaptation strategies surrounding HABs in Sechura and Paracas Bay, Peru. The analysis revealed several cross-cutting insights: coastal producers hold rich local knowledge of HABs but diverge in explaining mortality events. Socio-economic impacts in scallop mariculture, rather than public health effects, emerged as central among stakeholders. Most significantly, several adaptation strategies existed but remained uneven, with technological, informational, and institutional disparities leaving small-scale producers more exposed.

As exploratory study we focused on two bays, capturing perceptions at one point in time. Building on these findings, future research could extend the analysis across sectors and regions in Peru and use longitudinal or repeated studies to examine how perceptions, risk understandings, and adaptation strategies evolve in response to ENSO, seasonal variability, and longer-term climate change. The role of human-driven coastal pollution in HAB dynamics, alongside the political conflicts surrounding the attribution of HAB impacts, also needs closer attention – especially given that similar issues have emerged in other Latin American contexts such as Chile (Arriagada et al., 2025; Billi et al., 2022). Moreover, comparative social science research would additionally be valuable to identify both shared patterns and context-specific differences affecting HABs governance and vulnerability across contexts. Overall, our findings show that HABs are not only an ecological issue but raise questions of who bears the costs and who has the capacity to cope. As climate change intensifies pressure on already vulnerable coastal livelihoods, this dimension deserves greater attention in HAB research and governance, underscoring the need for responses that are more just and inclusive.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The study followed relevant ethical and data protection standards, including the principles of the DSGVO and applicable Peruvian regulations. Participants were informed about the aims and procedures of the project prior to participation. Participation was voluntary, participants could withdraw at any time and request the deletion of their data, and personal data were handled confidentially, stored securely, and anonymized prior to analysis. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

JM: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Validation, Visualization, Writing – original draft, Writing – review & editing. TC-M: Validation, Writing – original draft, Writing – review & editing. AA-V: Validation, Visualization, Writing – original draft, Writing – review & editing. AS: Investigation, Supervision, Validation, Writing – original draft, Writing – review & editing. MK: Conceptualization, Investigation, Methodology, Project administration, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The handling editor LR declared a past co-authorship with the author MK.

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The author(s) declared that generative AI was used in the creation of this manuscript. Generative AI technology (ChatGPT, GPT-5.4 Thinking, OpenAI) was used for language editing and proofreading of the manuscript. The authors reviewed and verified all suggested revisions and checked them for accuracy.

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The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2026.1844411/full#supplementary-material

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