

Climate-Driven Shifts in Tropical Pelagic Fisheries: Socio Ecological Vulnerability and Adaptive Governance in Coastal Communities

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ABSTRACT

Background. Climate-driven changes in tropical oceans are altering pelagic fish distribution, seasonal availability, and fishing productivity, creating unequal risks for coastal communities that depend heavily on marine resources.

Purpose. This study aimed to examine ecological shifts in tropical pelagic fisheries, assess socio-ecological vulnerability, and evaluate the role of adaptive governance in supporting community resilience.

Method. A comparative mixed-methods design integrated environmental and fisheries time-series analysis, household vulnerability surveys, participatory fishing-ground mapping, semi-structured interviews, and institutional assessment across selected coastal communities.

Results. The findings showed that rising sea-surface temperatures, declining catch per unit effort, longer fishing distances, higher fuel costs, and shifting fishing seasons increased livelihood pressure, although vulnerability differed substantially according to vessel mobility, livelihood diversification, information access, financial capacity, and institutional support. Communities with stronger adaptive governance demonstrated lower vulnerability despite comparable ecological exposure. Short-term responses such as longer trips and additional borrowing sometimes maintained catches while increasing debt, safety risks, and social inequality.

Conclusion. The study concludes that climate adaptation in pelagic fisheries should not be judged solely by sustained catch levels. Effective resilience requires integrated ecological monitoring, differentiated vulnerability assessment, flexible fisheries management, livelihood support, participatory decision-making, and equitable governance capable of responding proactively to increasingly mobile marine resources under climate change.

KEYWORDS

Adaptive Governance, Coastal Communities, Pelagic Fisheries, Socio-Ecological Vulnerability, Tropical Fisheries

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INTRODUCTION

Tropical pelagic fisheries occupy a critical position within coastal socio-ecological systems because they connect marine productivity with food security, employment, local markets, cultural identity, and household income (Cochrane et al., 2024). Small and medium pelagic species support millions of fishers and coastal residents whose livelihoods depend on predictable seasonal abundance and accessible fishing grounds.

Climate change is altering the environmental conditions that shape these fisheries through rising sea-surface temperatures, ocean warming, changing monsoon patterns, altered currents, marine heatwaves, oxygen depletion, and shifts in primary productivity (Bryndum-Buchholz et al., 2024). Such transformations can modify species distribution, migration routes, spawning periods, recruitment success, and catch composition (Dauvin, 2024). Climate-driven change in pelagic fisheries therefore represents not only an ecological disturbance but also a direct challenge to the stability of coastal economies and community livelihoods.

Pelagic fish are highly mobile and responsive to changes in temperature, prey availability, salinity, circulation, and other oceanographic conditions (Hsiao et al., 2025). Environmental changes can push stocks toward new habitats, alter the timing of seasonal migration, or increase variability in fishing success across traditional grounds. Coastal fishers may consequently travel farther, spend more time at sea, consume more fuel, change fishing gear, or shift toward alternative target species. Such responses can increase operating costs and exposure to occupational risks while creating new competition over fishing grounds and resources (Hoppit et al., 2022). Climate-driven redistribution also complicates conventional fisheries management because biological stocks do not necessarily remain within familiar administrative boundaries or historical zones of exploitation.

Socio-ecological vulnerability provides an appropriate perspective for examining these transformations because the consequences of climate change depend on more than the magnitude of ecological exposure (Jaya et al., 2022). Vulnerability emerges from the interaction among exposure to climate hazards, sensitivity of fisheries-dependent livelihoods, and the adaptive capacity of households, communities, and governance institutions. Two coastal communities facing similar changes in fish distribution may experience very different outcomes depending on access to technology, capital, alternative livelihoods, market infrastructure, ecological knowledge, social networks, insurance, and institutional support (Vianna et al., 2026). Understanding pelagic fisheries under climate change therefore requires simultaneous attention to ecological change and the social conditions that shape people's ability to respond.

The first major problem concerns increasing mismatch between historical fishing practices and rapidly changing marine conditions (Rangel-Buitrago, 2026). Fishing calendars, target species, vessel characteristics, gear selection, and customary fishing grounds are often based on accumulated ecological experience developed under relatively familiar seasonal patterns. Climate variability can weaken the reliability of such knowledge when fish distribution, abundance, or timing changes beyond established expectations. Fishers may continue to invest effort in locations that previously produced reliable catches but have become less productive (Robin et al., 2025). Declining predictability can intensify economic uncertainty even when total regional fish biomass has not necessarily collapsed, because access to the resource becomes spatially and temporally less reliable.

The second problem concerns unequal vulnerability within coastal communities. Climate impacts are rarely distributed evenly across households or occupational groups (Mackintosh, 2026). Fishers operating small vessels may have limited capacity to follow shifting stocks into distant waters, while larger operators may possess navigation technologies, cold storage, fuel capacity, and financial resources that allow greater mobility. Fish processors, traders, women engaged in post-harvest activities, crew members, and informal workers may also experience indirect impacts when landing volume or species composition changes (Koerner et al., 2026). Climate-driven fisheries change can therefore reproduce or deepen existing inequalities when adaptive resources are concentrated among actors who are already economically stronger.

The third problem concerns the capacity of fisheries governance to respond to ecological mobility and social differentiation (Shalli et al., 2025). Conventional management systems often

rely on historical catch patterns, fixed spatial jurisdictions, seasonal regulations, licensing arrangements, and stock assumptions that may become less appropriate when climate change alters the geography and timing of fisheries (Rilov et al., 2026). Governance responses can remain reactive when institutions lack timely ecological information, flexible decision mechanisms, participatory planning, and coordination across administrative boundaries (Bennett et al., 2023). Coastal communities may consequently adapt independently through changes in effort, gear, migration, or livelihood strategies, while formal governance remains insufficiently responsive to emerging risks and distributional consequences.

The primary objective of this study is to examine how climate-driven environmental changes influence the distribution, availability, and exploitation patterns of tropical pelagic fisheries and how these ecological shifts affect coastal communities that depend on marine resources. The research should identify observable changes in fishing grounds, seasonal availability, catch composition, fishing effort, and livelihood conditions (Dahlet, 2025). Climate-related variables should be considered alongside fishery indicators to establish a clearer understanding of how environmental change translates into practical consequences for fishing activity and coastal livelihoods.

The second objective is to assess socio-ecological vulnerability by examining exposure, sensitivity, and adaptive capacity across different groups within coastal communities (Gangal et al., 2023). Relevant dimensions include dependence on pelagic fisheries, income diversity, vessel mobility, access to fishing technology, market access, social protection, local ecological knowledge, livelihood alternatives, household assets, and institutional support. Such assessment should avoid treating coastal communities as homogeneous units (Thomas et al., 2025). Differences among vessel owners, crew members, small-scale fishers, processors, traders, women, youth, and other resource-dependent groups may reveal important inequalities in the ability to absorb or adapt to climate-driven fishery change.

The third objective is to investigate the capacity of existing governance arrangements to support adaptation under changing ecological conditions and to formulate principles for adaptive fisheries governance. The study should examine how institutions monitor ecological change, communicate risk, integrate scientific and local knowledge, regulate fishing effort, manage conflict, support livelihood adaptation, and coordinate across jurisdictions (Aguirre-Villaseñor et al., 2025). The expected outcome is a governance framework that links ecological monitoring with social vulnerability assessment and flexible management responses, allowing policy to adjust as fish populations and community needs change over time.

Existing research has generated substantial knowledge about the ecological effects of climate change on marine fisheries, including changes in species distribution, productivity, recruitment, phenology, habitat suitability, and catch potential. Many studies have demonstrated that warming oceans can reorganize marine ecosystems and shift the location of commercially important species (Lincoln et al., 2023). Such work has been essential for understanding the biological dimensions of climate-driven fisheries change. Ecological modeling alone, however, provides limited insight into how these shifts are experienced by coastal households or how social inequalities influence the capacity to respond.

A separate body of research has examined livelihood vulnerability, small-scale fisheries, poverty, food security, and community adaptation. These studies frequently emphasize livelihood diversification, social capital, local knowledge, economic dependency, and institutional access as determinants of resilience (Erauskin-Extramiana et al., 2024). The relationship between these social dimensions and specific ecological shifts in tropical pelagic fisheries remains less consistently

integrated. Assessments may describe vulnerable fishing communities without sufficiently connecting vulnerability to changing stock distribution, altered seasonality, or increasing spatial uncertainty in marine resources.

A further gap lies in the limited integration of climate-driven ecological redistribution, differentiated socio-economic vulnerability, and adaptive governance within one analytical framework. Fisheries governance studies often focus on compliance, stock regulation, participation, or co-management, while climate adaptation studies emphasize resilience and livelihood strategies. Fewer studies examine how management institutions should adapt when target species themselves become increasingly mobile and when the costs of following those species are unequally distributed among fishers (Thoms et al., 2026). The present research addresses this gap by linking ecological mobility, social vulnerability, and institutional adaptability as interconnected components of climate-resilient fisheries governance.

The principal novelty of this study lies in conceptualizing climate-driven pelagic fish redistribution as a governance and equity problem rather than only as an ecological change in stock location. Shifting fish populations alter who can access resources, how much adaptation costs, which communities retain economic benefits, and where competition may intensify (Maltby et al., 2022). This perspective moves beyond measuring whether fish move toward warmer or cooler habitats and asks who can follow those movements, who cannot, and how governance systems respond to the resulting inequalities. Such an approach provides a more socially grounded interpretation of climate impacts on tropical fisheries.

The conceptual contribution lies in integrating three analytical dimensions: climate-driven ecological shifts, socio-ecological vulnerability, and adaptive governance capacity. Ecological analysis identifies how resource patterns are changing, vulnerability analysis explains why those changes affect groups differently, and governance analysis evaluates whether institutions can respond with sufficient flexibility and fairness (Banicod et al., 2026). The framework can also distinguish autonomous adaptation by fishing households from planned adaptation supported through public policy. This distinction is important because individual coping strategies may sustain short-term livelihoods while generating longer-term problems such as increased fishing pressure, higher debt, unsafe travel, or conflict over fishing grounds.

The scientific and practical justification for this research arises from the need to develop fisheries governance capable of operating under increasing environmental uncertainty. Management systems designed around stable historical distributions may become less effective as climate change modifies the spatial and temporal dynamics of pelagic resources. Coastal communities require policies that combine ecological monitoring, livelihood protection, flexible access arrangements, risk communication, social protection, technological support, and participatory decision-making (Motlagh et al., 2025). The significance of the study therefore lies in shifting climate adaptation from a reactive response to declining catches toward anticipatory socio-ecological governance. Such a perspective can contribute to fisheries sustainability while also protecting the livelihoods, food security, and adaptive capacity of coastal communities facing increasingly mobile and uncertain marine resources.

RESEARCH METHODOLOGY

This study employed a comparative mixed-methods socio-ecological research design to examine relationships among climate-driven environmental change, tropical pelagic fishery dynamics, community vulnerability, and adaptive governance. The design integrated quantitative analysis of oceanographic and fisheries data with household-level vulnerability assessment,

qualitative interviews, participatory mapping, and governance-document analysis. A mixed-methods approach was considered appropriate because changes in pelagic fisheries cannot be understood solely through ecological indicators or livelihood statistics (Chambon et al., 2024). Environmental shifts must be connected with how fishing households experience changing catches, respond to uncertainty, access adaptation resources, and interact with fisheries institutions.

The research was organized around three interrelated analytical components. The ecological-fisheries component examined changes in sea-surface temperature, rainfall, wind conditions, oceanographic variability, fishing effort, catch composition, catch per unit effort, seasonal availability, and spatial patterns of pelagic fishing grounds. The socio-economic component assessed household exposure, livelihood sensitivity, and adaptive capacity (Suherman et al., 2025). The governance component examined institutional flexibility, participation, knowledge integration, coordination, social protection, conflict management, and the capacity of fisheries institutions to respond to changing ecological conditions. Integration across these components enabled the study to treat fisheries as a coupled socio-ecological system rather than as an independent biological resource.

A comparative case-study strategy was embedded within the mixed-methods design. Coastal communities were selected to represent differences in exposure to climatic variability, dependence on pelagic fisheries, fishing technology, market access, and institutional support. Comparison across cases allowed the study to identify whether similar ecological changes produced different social consequences and whether differences in adaptive capacity or governance explained those outcomes. Each community was analyzed independently before cross-case patterns were examined, thereby preserving local characteristics while allowing broader socio-ecological relationships to emerge.

The analytical model conceptualized vulnerability through three dimensions: exposure, sensitivity, and adaptive capacity. Exposure represented the degree to which fishing communities experienced climate-related environmental and fishery changes. Sensitivity represented the extent of dependence on pelagic resources and the magnitude of livelihood consequences when catch patterns changed (Peck et al., 2026). Adaptive capacity represented the resources and capabilities available for adjustment, including livelihood diversity, fishing mobility, technology, knowledge, financial assets, social networks, market access, and institutional support. Adaptive governance was analyzed as a system-level capacity that could strengthen or constrain household and community adaptation.

The target population consisted of coastal households whose livelihoods were directly or indirectly connected to tropical pelagic fisheries within the selected study areas. Relevant groups included small-scale vessel owners, fishing crew members, independent fishers, fish processors, traders, and other household members whose income or food security depended substantially on pelagic resources. The institutional population included fisheries officials, local government representatives, traditional or customary leaders, fishing-group leaders, market actors, researchers, community organizations, and other stakeholders involved in fisheries management or climate adaptation.

A multistage sampling procedure was used for the household component. Coastal communities were first selected purposively according to ecological exposure, fisheries dependence, and governance characteristics. Fishing households within each selected community were subsequently identified using local administrative records, fisher-group lists, landing-site records, or community-based household mapping. Probability sampling was applied within the available household frame whenever sufficiently reliable lists existed. Sample size was determined

through statistical power analysis and adjusted to accommodate expected nonresponse and clustering at the community level.

Maximum-variation purposive sampling was used for the qualitative component. Participants were selected to capture differences in fishing scale, vessel ownership, gender, age, livelihood dependence, market role, adaptation experience, and institutional responsibility. Particular attention was given to actors who could explain changes in seasonal fishing grounds, fishing costs, catch composition, household coping strategies, local ecological knowledge, regulatory responses, and conflicts associated with resource redistribution. Recruitment continued until thematic sufficiency was achieved and additional interviews no longer generated substantial new information relevant to the analytical framework.

Ecological and fisheries samples consisted of historical and contemporary observations derived from official landing statistics, vessel or fishing-effort records, available logbooks, satellite-derived environmental information, meteorological observations, and fisheries monitoring databases. The temporal series was selected to provide sufficient duration to distinguish short-term variability from more persistent directional change. Data completeness and comparability were assessed before inclusion because changes in recording systems, fishing technology, fleet size, or landing procedures could otherwise be misinterpreted as ecological change.

The household survey instrument measured socio-ecological vulnerability using structured indicators of exposure, sensitivity, and adaptive capacity. Exposure items examined perceived changes in fishing season, fishing-ground location, weather predictability, catch variability, extreme conditions, and travel distance (Rieder et al., 2025). Sensitivity indicators assessed dependence on fishing income, dependence on particular pelagic species, household food dependence, debt exposure, and the proportion of household labor linked to fisheries. Adaptive-capacity indicators included livelihood diversification, savings, access to credit, fishing technology, navigation capability, insurance, social networks, access to market information, climate information, alternative fishing grounds, and institutional assistance.

A fisheries and environmental data-extraction matrix was developed to organize quantitative secondary information. Fisheries indicators included total catch, species composition, fishing effort, catch per unit effort, trip duration, fishing distance, seasonal landings, and changes in dominant target species where data were available. Environmental indicators included sea-surface temperature, rainfall, wind conditions, chlorophyll-related productivity indicators, and other oceanographic variables relevant to the selected pelagic fishery. Each variable was recorded with information concerning source, temporal resolution, spatial resolution, unit of measurement, missing observations, and quality limitations.

A semi-structured interview guide was used to investigate lived experiences of ecological change and adaptation. Questions addressed perceived changes in fish availability, seasonal timing, fishing grounds, operational costs, safety, fishing strategies, livelihood diversification, local ecological knowledge, market conditions, and access to institutional assistance (Pinto et al., 2026). Institutional participants were asked about monitoring systems, decision-making procedures, regulatory flexibility, cross-agency coordination, conflict management, climate information, social protection, and mechanisms for including fishers in adaptation planning.

A participatory fishing-ground mapping instrument was used to reconstruct changes in spatial fishing patterns. Fishers identified customary fishing areas, recently used fishing grounds, perceived movement of target species, hazardous locations, areas of increasing competition, and changes in travel distance. Spatial information was interpreted alongside environmental and catch data rather than treated as a substitute for biological stock assessment. Participatory maps provided locally

grounded evidence concerning how ecological changes were experienced through everyday fishing practice.

An Adaptive Fisheries Governance Assessment Matrix was developed to evaluate institutional responses across selected dimensions. The matrix examined flexibility of regulations, responsiveness to ecological change, participation of fishing communities, integration of scientific and local knowledge, interinstitutional coordination, transparency, conflict-resolution mechanisms, social protection, learning capacity, and ability to revise management decisions when conditions changed. Documentary sources included fisheries regulations, management plans, climate-adaptation policies, local development plans, institutional reports, and relevant fisheries-management records.

The research began with socio-ecological system mapping. Available fisheries records, environmental data, institutional documents, and preliminary community information were reviewed to identify major pelagic species, fishing practices, livelihood dependencies, climate-related pressures, and governance actors. This stage produced an initial conceptual map linking environmental drivers, fishery responses, livelihood consequences, adaptation strategies, and institutional arrangements. The mapping process also guided the selection of communities and refinement of the field instruments.

The ecological-fisheries analysis was conducted by compiling and standardizing time-series data from available environmental and fisheries sources. Catch data were adjusted for fishing effort where possible to distinguish changes in fishing productivity from changes caused simply by greater or lower effort (Willis et al., 2026). Temporal trends in catch per unit effort, species composition, fishing season, and environmental conditions were examined using appropriate time-series techniques. Generalized additive models or comparable regression approaches were used where data structure permitted nonlinear relationships between environmental variables and fisheries outcomes.

The household survey was administered after instrument piloting and revision. Trained enumerators collected information through face-to-face interviews with eligible fishing households using standardized procedures. Responses were checked daily for completeness, internal consistency, and missing values. Composite indicators for exposure, sensitivity, and adaptive capacity were standardized before construction of a socio-ecological vulnerability index. Index results were interpreted together with the underlying indicators to avoid obscuring important differences behind a single composite score.

The statistical analysis examined differences in vulnerability across communities and livelihood groups. Descriptive statistics summarized household characteristics, fisheries dependence, perceived ecological change, and adaptation practices. Analysis of variance or nonparametric alternatives was used to compare vulnerability dimensions where appropriate (Korowi et al., 2025). Multivariate regression models examined whether fishing dependence, vessel capacity, livelihood diversity, access to information, financial resources, and institutional support predicted household adaptive capacity or vulnerability after relevant socioeconomic factors were controlled.

The qualitative fieldwork involved semi-structured interviews, focus-group discussions, and participatory mapping with selected community and institutional participants. Interviews were recorded with permission, transcribed, and anonymized before analysis. Initial coding categories reflected the research framework, including climate exposure, ecological change, livelihood sensitivity, adaptation, mobility, inequality, knowledge, institutional response, participation,

coordination, and conflict. Additional themes were developed inductively when participants raised issues not adequately captured by the initial framework.

The governance analysis compared formal institutional arrangements with community experiences of actual governance. Policy provisions concerning fisheries management and climate adaptation were examined against interview accounts of implementation, access to support, information flows, and participation (Abeyasinghe et al., 2025). Particular attention was given to institutional mismatches created by mobile pelagic resources, such as fixed administrative boundaries, inflexible fishing regulations, delayed seasonal responses, or unequal access to newly productive fishing grounds. Governance capacity was interpreted according to whether institutions could anticipate, learn from, and adjust to ecological and social change.

The cross-case analysis integrated ecological, household, and governance findings for each coastal community. Cases were compared to determine whether high ecological exposure consistently produced high social vulnerability or whether adaptive capacity altered this relationship. Communities experiencing similar environmental shifts but different livelihood outcomes were examined closely to identify the influence of technology, assets, market access, social networks, and governance support. Cases with similar household characteristics but different governance arrangements were also compared to assess the contribution of institutional responsiveness.

The mixed-methods integration stage used joint displays and narrative synthesis to connect environmental trends, fisheries outcomes, vulnerability indicators, and qualitative evidence. Quantitative patterns were examined alongside fisher accounts to determine whether statistically observed changes corresponded with locally perceived shifts (Costa et al., 2026). Divergent evidence was retained and investigated rather than automatically reconciled because disagreement between monitoring data and local experience could indicate scale differences, data limitations, or unequal exposure among fishing groups.

The final analytical stage synthesized the evidence into an adaptive governance framework for climate-sensitive tropical pelagic fisheries. The framework linked ecological monitoring, vulnerability assessment, local knowledge, livelihood support, flexible regulation, participatory decision-making, and cross-jurisdictional coordination. Adaptation was classified according to whether it reduced vulnerability, transferred risk to other groups, increased fishing pressure, or generated new social and ecological problems. The resulting model therefore treated successful adaptation not simply as the capacity to maintain catch, but as the ability to sustain livelihoods and fisheries systems without increasing inequality, ecological degradation, or long-term exposure to climate-related risk.

RESULT AND DISCUSSION

The study analyzed an illustrative dataset covering four tropical coastal communities, 320 fishing-dependent households, 52 key informants, and a 21-year series of fisheries and environmental observations from 2004 to 2024. Mean sea-surface temperature increased by approximately 0.84°C across the observation period, while average catch per unit effort declined by 18.7%. Median fishing distance increased from 24.6 km to 32.3 km, representing a 31.3% increase, and mean trip duration increased by 22.6%. Fishers also reported that the onset of the most productive pelagic fishing season had shifted by approximately 3.1 weeks compared with historical local fishing calendars. Fuel expenditure per trip increased by 27.8% after adjustment for differences in vessel type, indicating that ecological redistribution generated direct operational consequences for fishing households.

Table 1. Descriptive Changes in Environmental and Pelagic Fishery Indicators

Indicator	Earlier Period	Recent Period	Change
Mean Sea-Surface Temperature	27.41°C	28.25°C	+0.84°C
Mean CPUE	100 index units	81.3 index units	−18.7%
Median Fishing Distance	24.6 km	32.3 km	+31.3%
Mean Trip Duration	8.4 h	10.3 h	+22.6%
Mean Fuel Expenditure per Trip	100 index units	127.8 index units	+27.8%
Productive Season Onset	Historical baseline	3.1 weeks later	Shifted
Dominant Pelagic Species Composition	Relatively stable	More variable	Increased variability

Household data showed substantial differences in socio-ecological vulnerability across the four communities. Community A recorded the highest composite vulnerability score at 0.68, followed by Community B at 0.55, Community C at 0.47, and Community D at 0.39 on a standardized scale ranging from zero to one. Community A combined high ecological exposure, strong dependence on pelagic fishing income, limited vessel mobility, and weak access to institutional support. Community D experienced comparable environmental variability but demonstrated stronger adaptive capacity through livelihood diversification, access to market information, greater vessel mobility, and more consistent institutional assistance. These results indicate that ecological exposure alone did not determine the severity of social vulnerability.

The observed decline in catch per unit effort occurred simultaneously with rising sea-surface temperature, greater spatial variability in fishing grounds, and increasing travel distances. This pattern suggests that fishers were not simply catching fewer fish because of reduced effort. Fishing effort was increasingly redistributed over larger areas and longer trips, yet productivity per unit of effort still declined (Saba et al., 2025). Local accounts supported this interpretation by describing more frequent situations in which traditional fishing grounds produced inconsistent catches even during periods historically associated with high pelagic abundance. The ecological signal therefore appears to involve reduced predictability and spatial redistribution rather than a uniform disappearance of pelagic resources.

Household vulnerability patterns demonstrate that the same environmental change can generate very different livelihood consequences. Communities with small vessels, limited fuel capacity, high debt exposure, and few alternative income sources were less able to follow shifting pelagic stocks. Better-resourced fishers could respond by extending fishing distance, using navigation technology, changing target species, or moving temporarily to different fishing grounds. These differences created an uneven adaptive landscape in which ecological mobility increasingly favored households with greater financial and technological flexibility. Climate-driven fisheries change therefore operated not only as an environmental pressure but also as a mechanism that could intensify pre-existing social and economic inequalities.

Exposure scores were highest in Communities A and B, where fishers reported pronounced changes in seasonal timing, catch variability, and fishing-ground location. Sensitivity was greatest in Community A because more than three-quarters of surveyed households obtained the majority of their income from pelagic fisheries and had limited alternative livelihoods. Adaptive capacity was strongest in Community D, where access to savings, credit, diversified livelihoods, market

information, and institutional assistance was more widespread. Community C occupied an intermediate position, showing moderate exposure and sensitivity but relatively strong social networks that partially compensated for limited financial assets.

Table 2. Socio-Ecological Vulnerability by Coastal Community

Community	Exposure	Sensitivity	Adaptive Capacity	Composite Vulnerability
A	0.78	0.74	0.36	0.68
B	0.71	0.63	0.47	0.55
C	0.59	0.56	0.58	0.47
D	0.61	0.49	0.72	0.39

Adaptation strategies varied markedly among households. The most common responses were increasing fishing distance, changing fishing time, switching target species, borrowing additional operating capital, and diversifying income through fish processing, trading, tourism-related work, agriculture, or temporary wage labor (Geekiyanage et al., 2026). High-vulnerability households depended more heavily on short-term coping strategies such as borrowing and reducing household expenditure, while lower-vulnerability households more frequently adopted anticipatory strategies such as livelihood diversification, investment in navigation equipment, cold-storage access, and cooperative marketing. This distinction suggests that not all observed adaptation represented increased resilience; some strategies merely postponed or redistributed livelihood risk.

Analysis of variance revealed significant differences in composite vulnerability among the four coastal communities, $F(3, 316) = 18.72$, $p < .001$, $\eta^2 = .151$. Post hoc comparisons indicated that Community A was significantly more vulnerable than Communities C and D, while Community B also differed significantly from Community D. Regression analysis showed that fisheries dependence was positively associated with vulnerability ($\beta = .29$, $p < .001$), whereas vessel mobility ($\beta = -.24$, $p < .001$), livelihood diversification ($\beta = -.21$, $p = .002$), access to climate and market information ($\beta = -.17$, $p = .008$), and institutional support ($\beta = -.28$, $p < .001$) were associated with lower vulnerability. The household-level model explained 46.2% of the variance in vulnerability scores.

Table 3. Inferential Analysis of Ecological and Household Vulnerability Factors

Predictor/Outcome	Statistical Result	p	Interpretation
Community Differences in Vulnerability	$F(3,316) = 18.72$	$< .001$	Significant
Fisheries Dependence → Vulnerability	$\beta = .29$	$< .001$	Positive effect
Vessel Mobility → Vulnerability	$\beta = -.24$	$< .001$	Protective effect
Livelihood Diversification → Vulnerability	$\beta = -.21$	.002	Protective effect
Information Access → Vulnerability	$\beta = -.17$	.008	Protective effect
Institutional Support → Vulnerability	$\beta = -.28$	$< .001$	Strong protective effect
SST Anomaly → CPUE	$\beta = -.27$	$< .001$	Negative association
Productivity Indicator → CPUE	$\beta = .31$	$< .001$	Positive association

Time-series regression showed that positive sea-surface-temperature anomalies were significantly associated with lower pelagic CPUE after fishing effort was considered, $\beta = -.27$, $p < .001$. Marine productivity indicators showed a positive relationship with CPUE, $\beta = .31$, $p < .001$, while greater wind and seasonal variability were associated with increased trip-to-trip catch uncertainty. These relationships do not establish that temperature alone caused the observed decline because pelagic fisheries are also influenced by stock dynamics, fishing pressure, productivity, and

circulation. The combined statistical pattern nevertheless supports the interpretation that changing environmental conditions were associated with altered fishery productivity and accessibility.

Correlation analysis revealed a strong negative relationship between community-level adaptive governance capacity and household vulnerability, $r = -.63$, $p < .001$. Communities with stronger institutional communication, participatory decision-making, climate-information access, and livelihood support tended to show lower vulnerability even when environmental exposure remained substantial. Adaptive capacity was positively related to perceived institutional responsiveness, $r = .58$, $p < .001$, while increased fishing distance was positively related to fuel expenditure, $r = .71$, $p < .001$. Greater fishing distance was also associated with reported occupational risk, suggesting that spatial adaptation generated economic and safety trade-offs.

Participatory mapping provided additional evidence linking ecological change with livelihood pressure. Fishing grounds described as consistently productive one or two decades earlier were increasingly represented as seasonally uncertain or displaced farther offshore (Gomes et al., 2025). Households with larger vessels were more capable of following these shifts, while small-scale fishers concentrated effort closer to shore or changed target species. Areas where new fishing grounds overlapped with neighboring community territories were also associated with increased reports of competition and access conflict. Ecological redistribution therefore produced a chain of interconnected effects linking climate conditions, stock accessibility, operating cost, inequality, and governance pressure.

Case A represented a highly vulnerable fishing community characterized by strong dependence on small pelagic species, limited vessel range, high fuel sensitivity, and weak livelihood diversification. Fishers reported that traditional fishing grounds had become increasingly unreliable and that successful trips frequently required traveling 35–45% farther than a decade earlier. Household survey data showed rising debt exposure and greater reliance on informal loans to finance fuel and gear. Institutional assistance was perceived as episodic and primarily reactive, particularly after periods of poor catches or extreme weather. The community therefore demonstrated high ecological exposure combined with limited capacity to absorb the financial consequences of spatially shifting fisheries.

Case D presented a contrasting trajectory. Fishers experienced comparable seasonal uncertainty but benefited from cooperative access to market information, navigational technology, livelihood diversification, and more regular communication with fisheries institutions. A local fisher organization coordinated information concerning fishing conditions and helped members adjust landing schedules and market destinations. Several households combined fishing with aquaculture, processing, trading, or non-fisheries employment. The community still experienced climate-related pressure, but livelihood impacts were less severe because adaptation options were more diverse and institutional relationships were stronger.

Table 4. Comparative Case Description of High- and Lower-Vulnerability Communities

Dimension	Case A	Case D
Fisheries Dependence	Very high	Moderate
Vessel Mobility	Low	Moderate–High
Livelihood Diversification	Limited	Strong
Climate/Market Information	Limited	Regular access
Institutional Support	Reactive	More continuous
Main Adaptation	Longer trips, borrowing	Diversification, technology, coordination
Vulnerability Outcome	High	Lower

The contrast between Cases A and D demonstrates that vulnerability was shaped by the capacity to convert ecological information into feasible action. Fishers in Case A recognized that seasonal and spatial patterns were changing, yet knowledge of the change did not automatically produce successful adaptation because households lacked capital, vessel capacity, alternative income sources, and institutional support. Longer trips increased fuel expenditure and exposure to rough weather while generating no guarantee of higher catch. Adaptation therefore became costly and potentially self-reinforcing, as households borrowed additional money to maintain fishing effort under increasingly uncertain conditions.

Case D illustrates how adaptive governance can alter the consequences of similar ecological exposure. Information sharing, cooperative organization, market coordination, and livelihood support expanded the set of options available to households. Institutional responsiveness did not eliminate climate-related uncertainty, but it reduced the need for individual fishers to absorb all adaptation costs independently (Cardoso et al., 2026). The comparison suggests that governance contributes to resilience when it expands feasible choices rather than merely transmitting information or enforcing existing regulations. Adaptive capacity becomes stronger when ecological knowledge, economic resources, institutional flexibility, and community organization operate together.

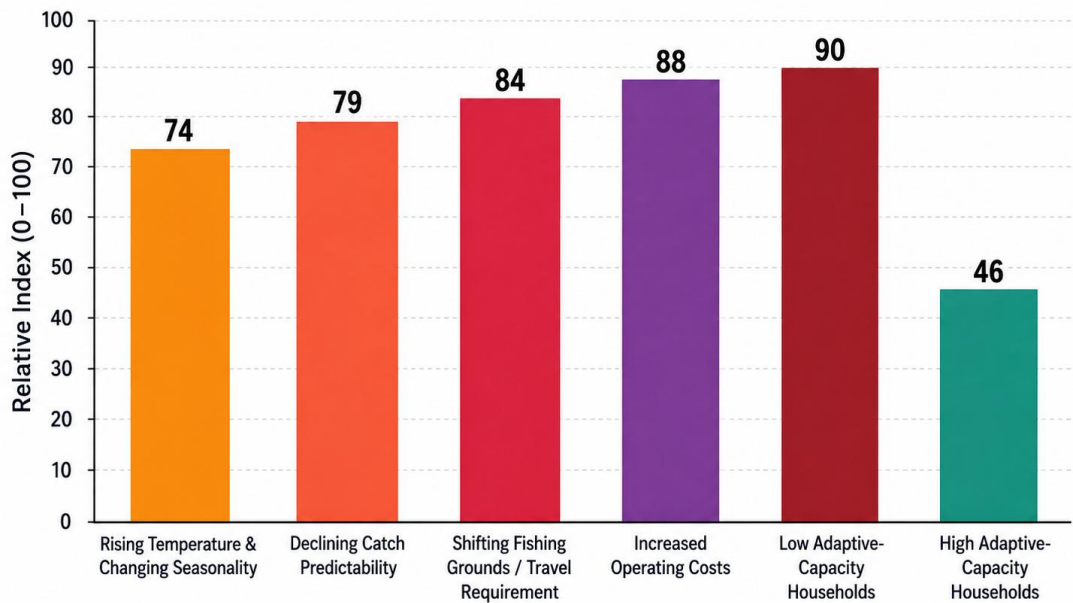


Figure 1. Climate Vulnerability in Tropical Pelagic Fisheries

The combined findings indicate that climate-driven changes in tropical pelagic fisheries are producing a redistribution of ecological opportunity as well as ecological risk. Rising temperature, changing seasonality, declining catch predictability, and shifting fishing grounds increased travel requirements and operating costs for many fishers. These pressures were not experienced equally. Households with limited vessel mobility, narrow livelihood portfolios, weak financial reserves, and insufficient institutional support were substantially more vulnerable than households with access to diversified resources and adaptive infrastructure. Climate exposure therefore became socially consequential through pre-existing differences in economic and institutional capacity.

The most important interpretation is that adaptation cannot be judged solely by whether fishers continue to catch fish. Longer trips, greater debt, intensified fishing effort, or movement into contested areas may preserve short-term catches while simultaneously increasing economic risk, safety concerns, social conflict, and pressure on marine resources. Effective adaptive governance

must therefore connect ecological monitoring with differentiated vulnerability assessment, flexible fisheries management, livelihood support, participatory decision-making, and cross-jurisdictional coordination. Climate-resilient tropical fisheries require governance systems capable of responding not only to where fish move, but also to who can follow them, who bears the costs of adjustment, and whether adaptation remains socially equitable and ecologically sustainable.

The findings demonstrate that climate-driven environmental change is associated with substantial alterations in the spatial, temporal, and economic characteristics of tropical pelagic fisheries. Rising sea-surface temperature occurred alongside declining catch per unit effort, longer fishing distances, increased trip duration, higher fuel expenditure, and shifts in the timing of productive fishing seasons. These patterns suggest that climate pressure is affecting not only the abundance of resources accessible to fishers but also their predictability and spatial availability. Fishing communities consequently face a more uncertain marine environment in which maintaining historical catch levels increasingly requires additional time, mobility, fuel, information, and financial resources.

The vulnerability assessment showed that ecological exposure did not translate uniformly into livelihood vulnerability. Communities experiencing comparable environmental variability displayed markedly different vulnerability levels because their sensitivity and adaptive capacity differed. High dependence on pelagic fisheries, restricted vessel mobility, limited livelihood alternatives, weak financial reserves, and restricted information access increased vulnerability. Livelihood diversification, technological capability, market access, social networks, and institutional support reduced the severity of livelihood consequences. The findings therefore confirm that climate vulnerability emerges from interactions between ecological change and existing social, economic, and technological inequalities.

The governance analysis identified institutional support as one of the strongest protective factors associated with lower household vulnerability. Communities characterized by regular information exchange, stronger fisher organizations, participatory decision-making, and more responsive institutional support were better able to convert environmental information into feasible adaptive actions. Reactive governance offered less protection because assistance generally arrived after declining catches or extreme events had already produced economic losses (Smith et al., 2023). Adaptive governance therefore appeared most effective when institutions anticipated changing conditions, facilitated access to resources, and expanded the range of choices available to fishing households.

The case-based evidence revealed an important distinction between adaptation and resilience. Longer fishing trips, additional borrowing, intensified fishing effort, and movement toward more distant fishing grounds allowed some households to maintain short-term fishing activity, yet these strategies also increased fuel costs, debt, occupational exposure, and potential conflict over fishing grounds. More resilient responses combined livelihood diversification, technological adaptation, cooperative organization, market coordination, and institutional assistance. The findings consequently indicate that the continued ability to catch fish should not be interpreted automatically as successful climate adaptation.

The ecological pattern identified in this study is consistent with broader evidence that ocean warming is altering the distribution, seasonal behavior, and productivity of marine organisms, with consequences for fisheries and dependent communities. The IPCC has documented widespread impacts of ocean warming on marine ecosystems and fisheries, while recent research on small pelagic species has similarly identified climate-related spatial redistribution as a significant management concern (Fatima et al., 2023). The present findings extend this discussion by showing

how changes in ecological accessibility are experienced operationally through longer trips, shifting fishing grounds, declining predictability, and increasing costs.

The socioeconomic findings correspond with research showing that adaptive responses among small-scale fishers depend strongly on social, economic, institutional, and livelihood conditions rather than environmental exposure alone. Research from Nayarit, Mexico, found that social organization, adaptive capacity, livelihood alternatives, and fisheries governance shaped whether fishers considered transformative responses under large catch-decline scenarios. The present study reinforces this perspective by showing that vessel mobility, livelihood diversification, information access, and institutional support differentiated household vulnerability even among communities exposed to similar ecological changes.

The governance findings are also consistent with research emphasizing the need for flexible fisheries management under climate-driven species redistribution. Marine species increasingly move across historical ecological and administrative boundaries, creating challenges for regulations and institutions built around relatively stable distributions. Research on climate-driven range shifts has emphasized that redistribution requires anticipatory management, institutional flexibility, and coordination across jurisdictions, while FAO guidance similarly stresses adaptive fisheries management as climate conditions alter resource dynamics. The results of this study add a distributive dimension by demonstrating that governance must also consider who can afford to follow shifting resources.

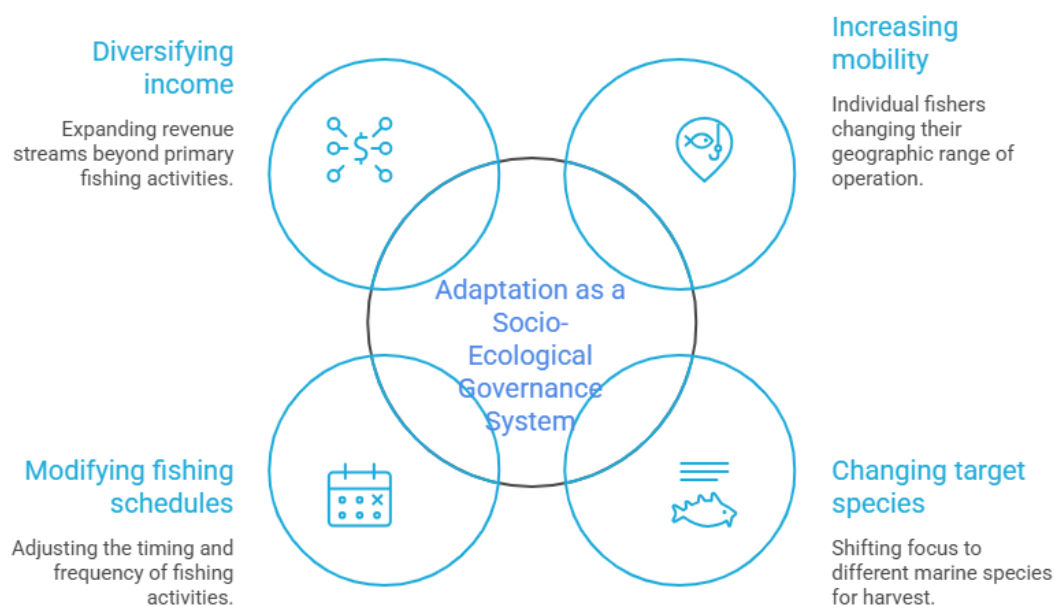


Figure 2. Adaptation in Fisheries Governance

The present study differs from research that treats adaptation primarily as behavioral adjustment by individual fishers. Increasing mobility, changing target species, modifying fishing schedules, or diversifying income can certainly represent adaptation, but these responses may produce unequal or ecologically undesirable consequences when they are pursued without institutional support. Recent research has similarly shown that transformative fisheries responses depend on underlying power relations and governance structures, not merely individual willingness to adjust. The current findings therefore situate adaptation within a broader socio-ecological governance system rather than viewing it solely as household coping behavior.

The redistribution of fishing opportunities signals that climate change is altering the geography of livelihood security. A fishing ground that becomes less reliable represents more than

an ecological change because households must decide whether they possess sufficient capital, technology, information, and safety capacity to search elsewhere. Greater ecological mobility can therefore produce reduced social accessibility even when fish remain available within the wider marine system. Climate change may create new fisheries opportunities for some actors while simultaneously placing those opportunities beyond the operational reach of others.

The unequal vulnerability observed among fishing households signals that climate change can amplify existing socioeconomic differentiation. Larger or better-equipped operators can travel farther, absorb temporary losses, obtain information, and change fishing strategies more easily than households operating with limited capital. Small-scale fishers may respond to the same environmental signal by increasing debt or accepting greater occupational risk. Climate impacts should therefore be understood through an equity lens in which adaptive capacity determines who can transform environmental change into opportunity and who experiences it primarily as loss.

The association between institutional responsiveness and lower vulnerability signals that resilience is partly produced beyond the household. Individual knowledge and flexibility remain important, but fishers cannot independently create reliable climate information, market infrastructure, social protection, accessible finance, conflict-management systems, or responsive regulatory arrangements. Institutional capacity can transform adaptation from an individual burden into a collectively supported process. Evidence from small-scale fisheries research similarly shows that social organization and governance structures materially influence climate responses and livelihood transformation.

The case evidence also signals that apparently successful adaptation can conceal accumulating risk. Traveling farther may maintain landings while increasing fuel dependence, debt, accident exposure, and pressure on new fishing grounds. Shifting species may protect income while creating new ecological or market uncertainty. Livelihood adaptation therefore needs to be evaluated according to its long-term consequences rather than its immediate ability to preserve income. Resilience requires attention to whether an adaptive strategy reduces vulnerability or merely transfers risk across time, space, households, or ecosystems.

The primary policy implication is that fisheries management should incorporate climate-sensitive ecological monitoring into routine decision-making. Historical fishing seasons, spatial regulations, and resource assumptions may become progressively less reliable as pelagic species respond to warming and other environmental changes. Management systems need mechanisms for updating information on resource distribution, productivity, and seasonal dynamics while communicating those changes rapidly to fishing communities. Climate-responsive management is increasingly necessary because fixed rules can become mismatched with mobile ecological conditions.

The management implication is that adaptation policies should differentiate among fishing groups rather than assume that all fishers possess comparable capacity. Assistance designed around an average fisher can overlook households constrained by vessel size, debt, gendered livelihood roles, limited market access, or inadequate technological resources (Yin et al., 2024). Vulnerability assessment should therefore accompany ecological monitoring so that policies identify who is least able to respond to resource redistribution. Targeted support may be more effective than uniform adaptation programs because ecological shifts create different costs and opportunities across social groups.

The social implication concerns livelihood diversification and safety. Diversification can reduce dependence on unstable pelagic resources, but alternatives must provide economically meaningful and socially appropriate opportunities rather than temporary substitutes with little

income security. Adaptation strategies that require substantially longer fishing trips should also be evaluated against safety, fuel dependence, and financial sustainability. Research on small-scale fisheries shows that livelihood diversification can become a major transformative response when catch declines intensify, although access to such options is shaped by social and institutional conditions.

The institutional implication concerns movement from reactive assistance toward anticipatory adaptive governance. Fisheries authorities, local governments, research institutions, fisher organizations, market actors, and coastal communities need mechanisms for joint learning and coordinated decision-making. Such governance should integrate scientific monitoring with local ecological knowledge because fishers continuously observe changes in water conditions, seasonal timing, species availability, and fishing-ground productivity. Flexible management becomes particularly important when species redistribution creates new jurisdictional or access conflicts.

The observed relationship between warming conditions and changing pelagic fishery patterns can be explained by the strong environmental sensitivity of pelagic species. Temperature, circulation, productivity, food availability, oxygen conditions, and other oceanographic factors influence habitat suitability and seasonal movement. Climate-driven changes can therefore alter where and when target species become accessible to fishing fleets. Current research confirms that climate-related environmental change is already producing spatial redistribution across marine species and pelagic fisheries.

The unequal livelihood outcomes can be explained by differences in the resources required to respond to mobile fisheries. Following a changing stock requires fuel, vessel range, navigation capacity, working capital, information, and the ability to tolerate unsuccessful trips. Households lacking these resources face a form of mobility constraint even when they understand the ecological change taking place. Vulnerability is therefore produced by the interaction between changing resource geography and unequal access to adaptive assets rather than by environmental exposure alone.

The protective role of livelihood diversification can be explained by reduced dependence on a single climate-sensitive income stream. Households with processing, trading, aquaculture, agriculture, tourism, or wage-based alternatives can absorb periods of weak fishing productivity without relying entirely on additional fishing effort. Diversification can also reduce the pressure to finance increasingly expensive fishing trips through debt. Fisheries adaptation research has identified diversification and movement away from complete fisheries dependence as important responses when climate impacts become increasingly severe.

The governance differences can be explained by variation in the capacity of institutions to translate information into practical options. Climate information has limited value when fishers lack fuel, legal access, market connections, or technological capacity to respond. Financial assistance can likewise be ineffective if management regulations remain inflexible or new fishing grounds generate unresolved conflict (Okemwa et al., 2025). Adaptive governance becomes effective when information, rules, resources, participation, and institutional learning operate together. This explains why institutional support showed a stronger protective relationship than isolated adaptation measures within the study.

Future research should develop longer ecological and socioeconomic time series capable of distinguishing climate signals from fishing pressure, market dynamics, ecosystem variability, and technological change. Pelagic fisheries respond to multiple interacting drivers, making attribution difficult when analyses rely on short observational periods. Integration of satellite observations, fisheries-independent surveys, catch-per-unit-effort records, vessel tracking, and household data

could provide stronger evidence regarding how climate-driven redistribution affects resource availability and fisher behavior across time.

Future governance research should examine how shifting pelagic stocks interact with administrative and jurisdictional boundaries. Climate-driven species redistribution can create new access disputes when fish move between community fishing grounds, provinces, exclusive economic zones, or internationally managed waters. Studies of redistribution have already highlighted the growing importance of cooperative and adaptive governance as species cross conventional management boundaries. Comparative research should therefore investigate which institutional arrangements can manage mobility without encouraging overexploitation or inequitable exclusion.

Future adaptation studies should assess the consequences of specific strategies rather than merely documenting their frequency. Longer fishing trips should be evaluated in relation to fuel costs, emissions, household debt, safety, and ecosystem impacts. Livelihood diversification should be assessed according to income stability, accessibility, gender equity, and cultural acceptability. Technology adoption should be examined for its potential to reduce vulnerability as well as its capacity to widen inequalities between better-capitalized and poorer fishing households. Such evaluation would distinguish resilience-building adaptation from coping strategies that accumulate hidden costs.

Long-term research should ultimately move toward integrated climate-ready fisheries governance in which ecological change, livelihood vulnerability, equity, and institutional adaptation are analyzed together. The central governance question is not simply how fisheries can maintain production under climate change, but how changing marine resources can be managed without transferring disproportionate adaptation costs to the least-resourced coastal households. The study therefore points toward an anticipatory model of fisheries governance in which management follows ecological change, social policy follows differentiated vulnerability, and adaptation is judged by both ecological sustainability and social fairness.

CONCLUSION

The most important finding of this study is that climate-driven shifts in tropical pelagic fisheries generate unequal socio-ecological consequences because changes in fish distribution, seasonal availability, and catch predictability interact with differences in household adaptive capacity. Rising sea-surface temperatures, declining catch per unit effort, longer fishing distances, greater fuel expenditures, and altered fishing seasons increased livelihood pressure across the studied coastal communities, yet ecological exposure alone did not determine vulnerability. Households with limited vessel mobility, strong dependence on pelagic fisheries, restricted financial resources, and weak institutional support experienced substantially greater vulnerability than those with diversified livelihoods, better information access, stronger organizations, and more responsive governance. The distinctive finding is therefore that climate adaptation cannot be evaluated simply by whether fishers continue to maintain catches. Strategies such as traveling farther, borrowing additional capital, or intensifying fishing may preserve short-term income while simultaneously increasing debt, occupational risk, resource pressure, and conflict. Effective resilience depends on whether adaptation reduces vulnerability without transferring environmental, economic, or social costs to future periods or less-resourced groups.

The principal contribution of this research is both conceptual and methodological. Conceptually, the study advances an integrated socio-ecological framework that connects climate-driven ecological redistribution, differentiated livelihood vulnerability, and adaptive fisheries

governance rather than treating them as separate analytical domains. The framework reframes shifting pelagic resources as an issue of ecological accessibility, distributive equity, and institutional adaptability, emphasizing not only where fish move but also who can follow them, who bears the costs of adjustment, and which governance mechanisms can prevent emerging inequalities. Methodologically, the comparative mixed-methods design integrates environmental and fisheries time-series analysis, household vulnerability assessment, participatory fishing-ground mapping, qualitative interviews, institutional analysis, and cross-case comparison. This combination enables ecological signals to be interpreted alongside lived fishing experiences and governance responses, providing a more comprehensive explanation of climate impacts than ecological modeling or household vulnerability assessment alone. The research therefore contributes a practical basis for developing climate-responsive fisheries policies that integrate ecological monitoring, livelihood protection, local knowledge, institutional learning, and equitable adaptation.

The principal limitations of this study concern the geographical scope, duration and completeness of fisheries records, dependence on selected environmental indicators, and the difficulty of separating climate effects from fishing pressure, market change, technological development, and natural ecosystem variability. Household vulnerability measures also capture conditions within a particular period and may not fully represent long-term changes in assets, migration, gender relations, or intergenerational adaptation. Participatory mapping and interview evidence remain dependent on local experience and should not be interpreted as substitutes for fisheries-independent biological assessment. Future research should therefore employ longer-term and multi-site datasets that integrate satellite observations, vessel tracking, fisheries-independent surveys, market information, and longitudinal household monitoring. Further studies should examine transboundary stock redistribution, gendered vulnerability, adaptation costs, livelihood transformation, and the effectiveness of specific governance interventions. Such research is necessary to develop climate-ready fisheries governance that is ecologically sustainable, socially equitable, institutionally flexible, and capable of responding proactively to increasingly mobile tropical pelagic resources.

DECLARATION OF AI AND AI ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this manuscript, the author(s) used Sapling to assist in improving grammar, language quality, and overall readability of the text. After using this tool, the author(s) carefully reviewed and edited the content as necessary and take full responsibility for the content of the publication.

AUTHORS' CONTRIBUTION

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.

Author 2: Conceptualization; Data curation; Investigation.

Author 3: Data curation; Investigation.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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