

System Dynamics-Based Assessment of Climate Resilience among Milkfish Aquaculture Households in Sibulue District, Bone Regency

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Abstract. Climate change increasingly threatens aquaculture livelihoods through extreme weather events, seasonal variability, and production uncertainty, potentially undermining household resilience and enterprise sustainability. This study aimed to assess aquaculture household resilience to climate change and evaluate alternative adaptation policies using a System Dynamics approach in Sibulue District, Bone Regency, Indonesia. A mixed-methods approach was employed involving 30 aquaculture households. Quantitative data were analyzed descriptively to construct resilience indicators, while qualitative findings were used to identify key factors and relationships influencing household resilience. These findings were integrated into a System Dynamics simulation model developed using Vensim to evaluate alternative policy scenarios. The overall household resilience index was 53.87, indicating a moderately resilient condition. The resilience perception index was 54.38, while the dependency resilience index reached 60.25 and was classified as resilient. The climate change adaptation and recovery adaptation indices were 47.08 and 53.75, respectively, both indicating moderately resilient conditions. Simulation results indicated that alternative policy scenarios generated different projected trajectories of household resilience and aquaculture enterprise sustainability under changing climatic conditions. These findings highlight the importance of integrated adaptation strategies combining financial support, government intervention, and technical adaptation measures to strengthen aquaculture household resilience and sustainability. However, the simulated outcomes represent model-based projections rather than empirically observed policy effects.

Keywords: aquaculture households, climate adaptation, resilience index, system dynamics, scenario analysis.

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INTRODUCTION

Climate change poses increasing challenges to the sustainability of aquaculture production systems through changes in temperature, rainfall patterns, seasonal variability, and the frequency and intensity of extreme weather events. These environmental pressures can affect aquaculture productivity, production costs, household income, and the long-term sustainability of aquaculture enterprises. The Intergovernmental Panel on Climate Change (IPCC) has emphasized that climate change affects food systems and natural resource-dependent livelihoods, while adaptive capacity plays a critical role in determining vulnerability and responses to climate-related risks (IPCC, 2022). Small-scale aquaculture households are particularly vulnerable because they often face limited access to financial resources, technology, climate information, infrastructure, and institutional support. Consequently, strengthening household resilience is essential for maintaining sustainable aquaculture production, securing livelihoods, and supporting aquatic food security.

Milkfish pond aquaculture is an important economic activity that contributes to household income in Bone Regency, South Sulawesi, Indonesia (BPS, 2024; DKP, 2024). The sustainability of pond aquaculture enterprises is influenced by various economic and technical production factors, including resource availability, production efficiency, and farm management practices (Pezi *et al.*, 2021; Suryadi *et al.*, 2021). However, the dependence of pond aquaculture on environmental conditions increases its exposure to climate-related disturbances. Changes in rainfall, temperature, and other environmental conditions may affect production stability, household income, and farmers' ability to maintain their enterprises (Galappaththi *et al.*, 2020; Fatahullah *et al.*, 2024). These challenges highlight the importance of understanding how small-scale milkfish aquaculture households respond to climate change and maintain their livelihoods under changing environmental conditions.

Household resilience is a multidimensional concept encompassing the capacity to withstand disturbances, adapt to changing conditions, and recover from adverse impacts while maintaining essential functions. In aquaculture households, resilience is influenced by interactions among exposure to climate-related hazards, sensitivity to environmental and economic disturbances, and adaptive capacity. Previous studies have demonstrated that aquaculture vulnerability is determined not only by environmental conditions but also by socioeconomic characteristics, access to resources, technological capabilities, knowledge, and institutional support (Handisyde *et al.*, 2017; Galappaththi *et al.*, 2020). Recent research has further highlighted the complex implications of climate change for aquaculture productivity and sustainability, particularly through changes in water temperature, hydrological conditions, environmental quality, and extreme weather events (Yadav *et al.*, 2024). Furthermore, the ability of small-scale aquaculture households to respond to these challenges depends on socioeconomic conditions, access to information, financial resources, and institutional support (Muthoka *et al.*, 2024; Hossain *et al.*, 2025). Therefore, assessing household resilience requires consideration of economic, environmental, social, and adaptive-capacity dimensions rather than relying exclusively on production indicators.

Previous studies have employed resilience indices to assess the vulnerability and adaptive capacity of fisheries and aquaculture communities. Index-based assessments are useful for identifying relatively strong and weak resilience dimensions and providing an overview of household conditions during a particular period. However, static resilience assessments may not adequately capture the dynamic relationships and feedback mechanisms among production, income, environmental disturbances, adaptive capacity, and recovery processes. For example, climate-related production losses may reduce household income, limiting farmers' financial capacity to implement adaptation measures. Reduced investment in adaptation may subsequently increase vulnerability to future disturbances and constrain household recovery. These interactions suggest that household resilience should be examined not only as a measurable condition but also as a dynamic process shaped by interdependent factors that evolve over time.

System Dynamics provides an analytical framework for examining complex relationships, feedback mechanisms, accumulation processes, and changes in system

behavior over time. Originally developed by [Forrester \(1961\)](#), this approach enables researchers to represent interactions among system components and explore their potential responses under alternative conditions. System Dynamics has been applied in fisheries and aquaculture research to examine production processes, resource management, sustainability, and policy interventions. Recent research has also highlighted the importance of feedback mechanisms in understanding how aquaculture systems respond to external pressures and management decisions ([Gudbrandsdottir et al., 2025](#)). Through causal loop diagrams (CLDs) and stock and flow diagrams (SFDs), System Dynamics can provide a structured representation of relationships among economic, environmental, production, and adaptation variables. Furthermore, simulation-based scenario analysis allows alternative policy interventions to be compared in terms of their projected effects on system behavior.

Despite advances in aquaculture resilience assessment and dynamic modeling, further research is needed to integrate household-level resilience indicators with the feedback relationships linking production, economic conditions, environmental pressures, adaptive capacity, and recovery. Existing index-based assessments provide valuable information about resilience conditions, but their integration into dynamic simulation models remains an area requiring further investigation. Moreover, context-specific evidence concerning the resilience of small-scale milkfish aquaculture households in Indonesia, particularly through the simulation of alternative adaptation policies, remains limited. Addressing this gap requires an approach that combines empirical household resilience assessment with dynamic modeling to examine how interactions among system components may influence resilience trajectories under different policy scenarios.

This study addresses these gaps by integrating multidimensional household resilience indicators with a System Dynamics framework to investigate the potential trajectories of milkfish aquaculture household resilience under alternative adaptation scenarios. The research focuses on two milkfish farmer groups comprising 30 respondents in Sibulue District, Bone Regency, Indonesia. By combining quantitative resilience assessment with qualitative information on the relationships among influencing factors, the study develops a dynamic representation of household resilience and examines the projected implications of alternative adaptation policies. The contribution of this study lies in linking household-level resilience measurement with feedback-based simulation to support the identification of potentially effective adaptation strategies. This approach offers a basis for understanding the interactions between household resilience and aquaculture enterprise sustainability while informing policy considerations for small-scale aquaculture communities.

Accordingly, this study aimed to (1) assess the resilience of milkfish aquaculture households to climate change using multidimensional resilience indicators, (2) develop a System Dynamics model incorporating CLDs and SFDs to represent relationships and feedback mechanisms among production, economic, environmental, adaptive-capacity, and recovery factors, and (3) evaluate alternative adaptation policy scenarios to identify interventions with the greatest potential to strengthen household resilience and aquaculture enterprise sustainability in Sibulue District, Bone Regency, Indonesia.

METHODS

Research Design and Study Area

This study employed a mixed-methods approach using an exploratory sequential design (QUAL → QUAN), in which qualitative data collection and analysis preceded the quantitative stage. The qualitative phase involved in-depth interviews, focus group discussions (FGDs), and field observations to identify climate-related disturbances, household socioeconomic conditions, adaptation strategies, recovery capacity, and potential causal relationships influencing the resilience of milkfish aquaculture households. The findings informed the development of resilience indicators and the subsequent quantitative data collection.

The quantitative phase involved a household survey designed to assess resilience using the identified indicators. Findings from both phases were subsequently integrated

into the development of a System Dynamics model to represent relationships among resilience factors and explore potential changes under alternative policy scenarios. This sequential integration followed the general principles of exploratory sequential mixed-methods research described by [Creswell and Plano Clark \(2018\)](#). The study was conducted in 2026 in Sibulue District, Bone Regency, South Sulawesi, Indonesia. The study area was purposively selected because pond aquaculture represents an important livelihood activity in the district, where environmental pressures and changing climatic conditions may affect aquaculture productivity and household enterprise sustainability.

Respondents and Unit of Analysis

The unit of analysis was the milkfish aquaculture household. A total of 30 households belonging to two aquaculture farmer groups were selected through purposive sampling. This sampling technique was employed to identify respondents with characteristics and experiences relevant to the research objectives ([Ahmad & Wilkins, 2025](#)). The primary respondents were household heads or household members directly involved in milkfish aquaculture, production management, and enterprise decision-making. Respondents were selected based on five criteria: (1) direct involvement in milkfish aquaculture activities, (2) experience of at least one production cycle, (3) participation in production or enterprise management decisions, (4) knowledge of household production conditions, income, and environmental changes, and (5) willingness to participate and provide the required information.

These criteria were intended to ensure that respondents could provide relevant information on household socioeconomic characteristics, aquaculture production, adaptation strategies, and recovery capacity. The household-level approach was adopted because adaptive capacity and responses to climate-related disturbances may differ among aquaculture households ([Galappaththi et al., 2020](#)). In addition to household respondents, key informants included fisheries extension officers, aquaculture farmer group leaders, village government representatives, and community leaders. Key informants were not included in the calculation of the household resilience index. Instead, their information was used to triangulate household responses, review proposed causal relationships, identify adaptation and recovery mechanisms, and inform the formulation of alternative policy scenarios.

Data Collection and Integration

Data were collected through in-depth interviews, FGDs, field observations, and structured questionnaires. Qualitative data were used to explore household experiences of climate variability, perceived environmental changes, adaptation practices, factors supporting or constraining recovery, and interactions among variables influencing resilience. Quantitative data were collected through household questionnaires to assess resilience using the indicators developed for the study. These data provided the basis for calculating dimension-specific and overall household resilience indices.

Data integration was conducted sequentially at three stages. First, qualitative findings informed the identification of resilience indicators and relationships among relevant variables. Second, quantitative survey data were used to assess household resilience across the identified dimensions. Third, the qualitative and quantitative findings were integrated to inform the structure and variables of the System Dynamics model. Through this approach, the resilience index provided a quantitative description of household conditions, while the System Dynamics model represented potential interactions and feedback mechanisms that could influence changes in resilience over time.

Assessment of Aquaculture Household Resilience

The resilience of milkfish aquaculture households was assessed using the Aquaculture Household Resilience Index (AHRI). The index comprised four dimensions: (1) perceptions of climate change, (2) socioeconomic conditions and household dependency, (3) adaptive capacity, and (4) recovery capacity.

A multidimensional approach was adopted because household resilience is influenced by interactions among social, economic, environmental, and institutional factors (Cutter *et al.*, 2010). Indicator information was collected through questionnaires and interviews using Likert-scale assessments.

Indicators were interpreted according to their expected relationship with household resilience. Positive indicators represented conditions associated with greater resilience, including income diversification, access to financial resources, aquaculture experience, training participation, adoption of adaptive technologies, and institutional support. Negative indicators represented conditions associated with greater vulnerability, including exposure to climate-related disturbances, production losses, and dependence on a single income source. Indicator scores were adjusted according to their direction so that higher scores consistently represented greater resilience.

The resilience index was expressed on a scale of 0–100, with higher values indicating greater household resilience. The index incorporated socioeconomic, adaptive-capacity, and recovery-capacity characteristics, consistent with multidimensional approaches applied in fisheries and aquaculture resilience research (Ochieng *et al.*, 2024; REDE *et al.*, 2024). Index values were classified into five categories: non-resilient (0–20), low resilience (>20–40), moderately resilient (>40–60), resilient (>60–80), and highly resilient (>80–100). The four dimension-specific indices were aggregated using an arithmetic mean to obtain the overall AHRI. Accordingly, each dimension contributed equally to the composite index.

Resilience Indicators

The indicators used to assess milkfish aquaculture household resilience were organized into four dimensions, as presented in Table 1.

Table 1. Indicators and Parameters for Assessing the Resilience of Milkfish Aquaculture Households

No.	Dimension	Parameters/Indicators
1	Perceptions of climate change	Perceptions of climate change, seasonal variability, water quality, and changes in water temperature
2	Socioeconomic conditions and household dependency	Aquaculture experience, number of household dependents, primary and supplementary livelihoods, household income, production costs, production output, and environmental and climatic conditions
3	Adaptive capacity	Adoption of adaptive aquaculture technologies and equipment, livelihood diversification, use of quality seed, improvements in water channels or water supply systems, and adjustments to aquaculture management practices
4	Recovery capacity	Participation in training, access to credit and financial resources, cooperation among farmer group members, government assistance, and institutional support

System Dynamics Modeling

The household resilience indices and qualitative findings were used to develop a System Dynamics model representing interactions among the factors influencing milkfish aquaculture household resilience. Model development involved constructing a Causal Loop Diagram (CLD) and a Stock and Flow Diagram (SFD). The CLD was developed to represent hypothesized causal relationships and reinforcing or balancing feedback mechanisms among variables. These relationships included interactions among climate-related pressures, pond environmental conditions, milkfish productivity, household income, financial resources, adaptive capacity, and recovery capacity.

The SFD was subsequently used to represent the accumulation and changes of relevant system variables over time. The model structure was informed by interviews, FGDs, field observations, household resilience indicators, and information obtained from key informants. System Dynamics modeling was conducted using Vensim to explore how interactions among system components could influence household resilience under

different adaptation scenarios. This approach enabled the study to examine potential resilience trajectories beyond the static conditions represented by the household survey.

Policy Scenario Simulation

The System Dynamics model was used to evaluate three policy scenarios representing different levels of adaptation intervention. The first scenario was the baseline scenario, representing the existing conditions of milkfish aquaculture households and serving as the reference for comparison. The second was the moderate adaptation scenario, representing improvements in household adaptive capacity and responsiveness to climate-related pressures. The third was the high adaptation scenario, representing stronger adaptation interventions and enhanced recovery mechanisms.

Scenario outcomes were compared based on projected changes in household resilience, aquaculture productivity, household income, adaptive capacity, and recovery capacity. The simulation results were used to examine differences in system behavior across the scenarios and identify adaptation interventions with the potential to strengthen household resilience and aquaculture enterprise sustainability. The projected outcomes were interpreted as scenario-dependent model results rather than empirically observed effects of implemented policies.

RESULTS AND DISCUSSION

Aquaculture Household Resilience Index

The assessment results indicated that the resilience of milkfish aquaculture households in Sibulue District was characterized by four dimensions: perceptions of climate change, household dependency, adaptive capacity, and recovery capacity. Resilience levels were classified into five categories based on the index intervals established in this study: non-resilient (0–20), low resilience (>20–40), moderately resilient (>40–60), resilient (>60–80), and highly resilient (>80–100). The dimension-specific resilience indices and their corresponding classifications are presented in [Table 2](#).

Table 2. Resilience Index Values by Dimension

Resilience dimension	Index value	Category
Perceptions of climate change	54.38	Moderately resilient
Household dependency	60.25	Resilient
Climate change adaptation	47.08	Moderately resilient
Recovery capacity	53.75	Moderately resilient
Arithmetic mean	53.87	Moderately resilient

The overall Aquaculture Household Resilience Index (AHRI) was 53.87, calculated as the arithmetic mean of the four dimension-specific indices. This value placed milkfish aquaculture households in the moderately resilient category, suggesting that they possessed some capacity to respond to environmental and socioeconomic pressures but still had opportunities to strengthen their adaptive and recovery capacities. The household dependency dimension recorded the highest index (60.25), corresponding to the resilient category, whereas climate change adaptation had the lowest index (47.08), indicating moderate resilience. These differences suggest that adaptive capacity represents a relatively weaker dimension of household resilience compared with the other dimensions assessed.

The relatively low adaptation index highlights potential limitations in households' capacity to adopt appropriate technologies, diversify livelihood activities, and implement adaptation measures. Financial resources and production-related factors may contribute to these constraints, as previous research has emphasized the importance of capital and production inputs in determining income from milkfish pond aquaculture ([Pezi et al., 2021](#)). Nevertheless, the dimension-specific indices describe relative resilience conditions rather than establishing direct causal relationships among household dependency, financial capacity, and adaptation outcomes. Strengthening access to financial resources, technical assistance, and adaptive aquaculture practices may therefore be important considerations for improving household resilience.

Household Perceptions of Climate Change

The climate change perception index was 54.38, placing this dimension in the moderately resilient category. This finding suggests that milkfish aquaculture households demonstrated a moderate level of awareness of climate-related environmental changes. However, differences among the individual perception indicators indicate that awareness was not uniform across the environmental factors assessed. The indicator scores are presented in [Table 3](#).

Table 3. Indicator Scores for Perceptions of Climate Change

Parameter	Score	Interpretation
Seasonal changes	81.70	High
Water quality	51.70	Moderate
Climate change issues	46.70	Moderate
Temperature	37.50	Low
Perception index	54.38	Moderately resilient

Perceptions of seasonal changes received the highest score (81.70), indicating that respondents were relatively more aware of seasonal variability than other climate-related environmental factors. This finding may reflect the importance of seasonal conditions in milkfish pond aquaculture activities, particularly in determining production schedules and managing pond environments. In contrast, temperature received the lowest score (37.50), suggesting comparatively limited awareness or recognition of temperature-related changes. Water quality (51.70) and general climate change issues (46.70) received moderate scores, indicating differences in respondents' perceptions across environmental indicators.

These findings highlight the importance of strengthening farmers' understanding of climate-related environmental changes and their potential implications for aquaculture management. Temperature and water quality are important environmental factors that can influence the physiological condition of cultured organisms, pond productivity, and production stability. Water quality dynamics, including changes in total suspended solids, have also been associated with pond environmental conditions and ecosystem productivity ([Lestariji et al., 2026](#)). However, the perception scores do not directly establish whether farmers regularly monitor these parameters or apply specific management responses. Therefore, efforts to improve resilience in this dimension could focus on strengthening climate literacy, facilitating access to climate and environmental information, and promoting practical monitoring of temperature and water quality to support aquaculture decision-making.

Household Dependence on Aquaculture Enterprises

The household dependency index was 60.25, placing this dimension in the resilient category based on the classification criteria established in this study. Several economic and production-related indicators recorded relatively high scores, particularly primary livelihood (91.67), household income (88.33), and aquaculture production (86.67). In contrast, environmental indicators, including salinity (25.00), pH (38.33), and water temperature (43.33), received considerably lower scores. This pattern highlights differences between the relatively favorable economic and production-related indicators and the weaker environmental components of household resilience.

The high scores for primary livelihood, household income, and production suggest that aquaculture activities play an important role in supporting household economic conditions. However, dependence on aquaculture as a primary source of income may also increase household vulnerability when production is disrupted by climate-related disturbances. The relatively low scores for salinity, pH, and water temperature further indicate that environmental conditions represent areas requiring attention in aquaculture resilience assessment. Nevertheless, these indicator scores should not be interpreted as direct evidence of deteriorating water quality without corresponding environmental measurements.

Water quality and environmental variability are important considerations in aquaculture management because they can influence the growth, health, and survival of cultured organisms and overall production stability. Research on intensive shrimp aquaculture has demonstrated relationships between water quality dynamics, phytoplankton community structure, and pond ecosystem conditions (Lestariaji *et al.*, 2026). Although these findings provide relevant insights into pond ecosystem management, their applicability to milkfish aquaculture should be considered in relation to differences in culture systems and environmental conditions. Furthermore, dependence on a single livelihood source may increase exposure to economic shocks when aquaculture production declines. Livelihood diversification has been identified as a potential strategy for reducing vulnerability and strengthening household well-being (Janmaimool *et al.*, 2025). Therefore, efforts to improve household resilience should consider not only increasing aquaculture productivity and income but also diversifying income sources and strengthening environmental risk management.

Adaptive Capacity to Climate Change

The climate change adaptation index was 47.08, representing the lowest score among the four resilience dimensions and placing adaptive capacity in the moderately resilient category. This finding suggests that adaptation-related characteristics were relatively weaker than the other dimensions assessed. The individual indicator scores are presented in Table 4.

Table 4. Adaptive Capacity Indicators of Milkfish Aquaculture Households

Parameter	Score
Water-channel improvement	64.17
Use of improved seed	57.50
Livelihood diversification	41.67
Adoption of equipment and technology	25.00
Adaptation index	47.08

Water-channel improvement received the highest score (64.17), followed by the use of improved seed (57.50). These findings indicate that water-management improvements and seed selection were relatively stronger components of household adaptation than the other practices evaluated. Improvements in water channels may support pond-water management and help households respond to environmental variability. However, the extent to which these improvements reduce climate-related production risks was not directly evaluated.

Livelihood diversification received a lower score (41.67), while the adoption of equipment and technology recorded the lowest score (25.00). These results indicate relatively limited adoption of technological adaptation measures and diversification practices among the surveyed households. Potential constraints may include limited financial resources, access to appropriate technologies, technical knowledge, and institutional assistance. Nevertheless, the relative contribution of these factors cannot be established from the index scores alone.

The findings suggest that strengthening adaptive capacity requires a broader approach extending beyond improvements in aquaculture production. Potential measures include facilitating access to appropriate aquaculture technologies, improving water-quality management, supporting livelihood diversification, and increasing access to financial and technical assistance. Such measures may help households respond more effectively to environmental disturbances and reduce their vulnerability to climate-related production risks.

Recovery Capacity

The recovery capacity index was 53.75, placing this dimension in the moderately resilient category. Recovery capacity was assessed through indicators related to financial assistance, community cooperation, training participation, and government support. The indicator scores are presented in Table 5.

Table 5. Recovery Capacity Indicators of Milkfish Aquaculture Households

Parameter	Score
Access to financial assistance	73.33
Community mutual cooperation	66.67
Training participation	42.50
Government support	32.50
Recovery index	53.75

Access to financial assistance recorded the highest score (73.33), followed by community mutual cooperation (66.67). These results suggest that financial assistance and community-based cooperation represent relatively strong components of household recovery capacity. Access to financial resources may help households manage production-related expenditures and respond to unexpected losses, while community cooperation may facilitate the exchange of information, resources, and assistance during periods of disruption.

In contrast, training participation (42.50) and government support (32.50) received lower scores, indicating relatively weaker institutional and capacity-building components. These findings suggest that household recovery capacity may benefit from greater access to technical training, extension services, and government assistance. However, the index values do not directly establish the effectiveness of existing financial assistance or institutional programs in accelerating household recovery.

The differences among recovery indicators provide relevant considerations for strengthening household resilience. Financial resources, community cooperation, technical knowledge, and institutional support may interact with aquaculture productivity, adaptive capacity, and recovery processes. These potential relationships were subsequently incorporated into the conceptual development of the System Dynamics model to examine how changes in selected factors could influence projected household resilience under alternative adaptation scenarios.

Causal Loop Diagram and System Dynamics Structure

The results of the household resilience assessment provided an empirical basis for identifying key variables in the development of the Causal Loop Diagram (CLD). The CLD was constructed to represent hypothesized causal relationships and feedback mechanisms among economic, social, environmental, production, adaptation, and recovery variables. The relationships represented in the diagram were informed by the resilience indicators and qualitative findings from interviews, focus group discussions, field observations, and key informants (Figure 1).

The CLD served as a conceptual framework for examining how changes in one component of the aquaculture household system could potentially influence other components through reinforcing or balancing feedback mechanisms. These relationships provided the foundation for developing the Stock and Flow Diagram (SFD) and conducting subsequent System Dynamics simulations under alternative policy scenarios.

Within the proposed system structure, increasing climate-related pressures may adversely affect pond environmental conditions and increase the risk of milkfish mortality, potentially reducing aquaculture production. Declining production may subsequently reduce household income and financial assets, thereby limiting the resources available for adaptation investments. Reduced investment capacity may weaken adaptive capacity and increase household vulnerability to subsequent environmental disturbances. These interconnected relationships may create a reinforcing feedback mechanism in which production losses and financial constraints amplify household vulnerability over time.

Conversely, improved access to credit, government assistance, infrastructure development, and appropriate aquaculture technologies may strengthen adaptive capacity and support production performance. Higher production may contribute to increased household income and financial assets, providing additional resources for

further adaptation investments. This process may establish a reinforcing recovery mechanism in which improvements in productive and financial capacity support continued adaptation. However, the identification of reinforcing and balancing feedback loops depends on the direction and polarity of the causal relationships represented in the complete Causal Loop Diagram (CLD).

The CLD therefore provides a conceptual representation of how aquaculture household resilience may emerge from dynamic interactions among climate-related pressures, pond environmental conditions, production, economic resources, and adaptation interventions. These relationships represent hypothesized causal mechanisms derived from the study findings and were subsequently incorporated into the development of the Stock and Flow Diagram (SFD) for scenario simulation.

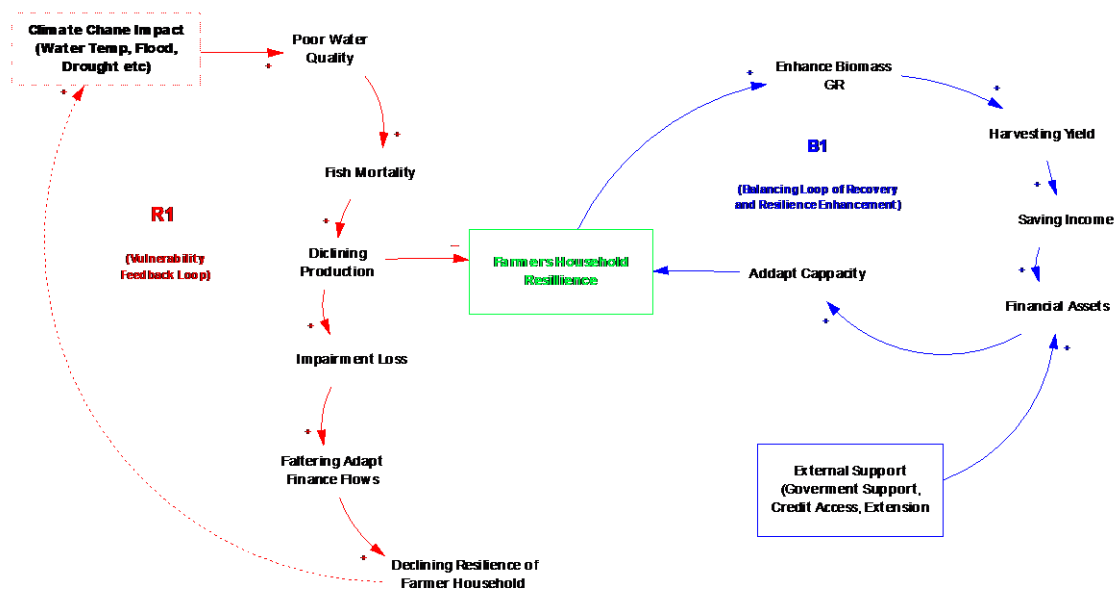


Figure 1. Causal Loop Diagram (CLD) of Aquaculture Household Resilience to Climate Change in Sibulue District, Bone Regency.

Dynamic Model Simulation

The Stock and Flow Diagram (SFD) was used to simulate potential changes in milkfish aquaculture household resilience under three alternative policy scenarios during 2026–2031 (Figure 2). The simulations explored possible system trajectories based on the model structure, parameter values, and scenario assumptions rather than providing definitive predictions of future conditions. The model had not undergone a complete set of validation procedures, including extreme-condition testing, behavior reproduction testing, sensitivity analysis, and uncertainty analysis. Consequently, the simulation results were interpreted as exploratory projections intended to compare potential system responses under different adaptation assumptions. The simulation outcomes for aquaculture production, household income, financial assets, and household resilience are summarized in Table 6.

Table 6. Comparison of Initial and Final Simulation Conditions Under Three Policy Scenarios (2026–2031)

Scenario	Harvest (kg)	Income (IDR million)	Financial assets (IDR million)	Resilience index (0–100)
Current	1,886 → 1,778	40.69 → 38.37	50.00 → 11.71	53.83 → 40.70
Moderate adaptation	1,886 → 2,350	40.69 → 50.70	50.00 → 154.63	53.83 → 89.70
High adaptation	1,886 → 2,584	40.69 → 55.74	50.00 → 231.49	53.83 → 100.00

Note: Values represent simulated conditions in 2026 and 2031, respectively.

Under the Current Scenario, all major indicators exhibited declining trajectories. Simulated aquaculture production decreased from 1,886 kg in 2026 to 1,778 kg in 2031, while household income declined from IDR40.69 million to IDR38.37 million. Financial assets decreased substantially from IDR50.00 million to IDR11.71 million. The resilience index also declined from 53.83 to 40.70. Based on the classification criteria established in this study, the final value remained within the moderately resilient category, although it approached the lower boundary of this classification. These projected declines suggest that, under the baseline assumptions, household economic resources and resilience may weaken in the absence of additional adaptation interventions.

Under the Moderate Adaptation Scenario, simulated aquaculture production increased from 1,886 kg to 2,350 kg, while household income rose from IDR40.69 million to IDR50.70 million by 2031. Financial assets increased from IDR50.00 million to IDR154.63 million, accompanied by an increase in the resilience index from 53.83 to 89.70. The final resilience value was classified as highly resilient. These results suggest that the combined adaptation measures represented in the scenario may generate more favorable trajectories of production, economic capacity, and household resilience than those projected under the Current Scenario.

The High Adaptation Scenario generated the highest final values across all simulated indicators. Aquaculture production increased to 2,584 kg, household income reached IDR55.74 million, and financial assets increased to IDR231.49 million by 2031. The simulated resilience index reached 100.00, representing the upper boundary of the model's resilience scale. This result should not be interpreted as evidence of perfect household resilience under actual conditions. Rather, it indicates that the simulated resilience measure reached its maximum permitted value under the assumptions and parameter settings of the High Adaptation Scenario. The results suggest that stronger adaptation interventions may generate more favorable simulated outcomes, although their practical effectiveness remains to be empirically evaluated.

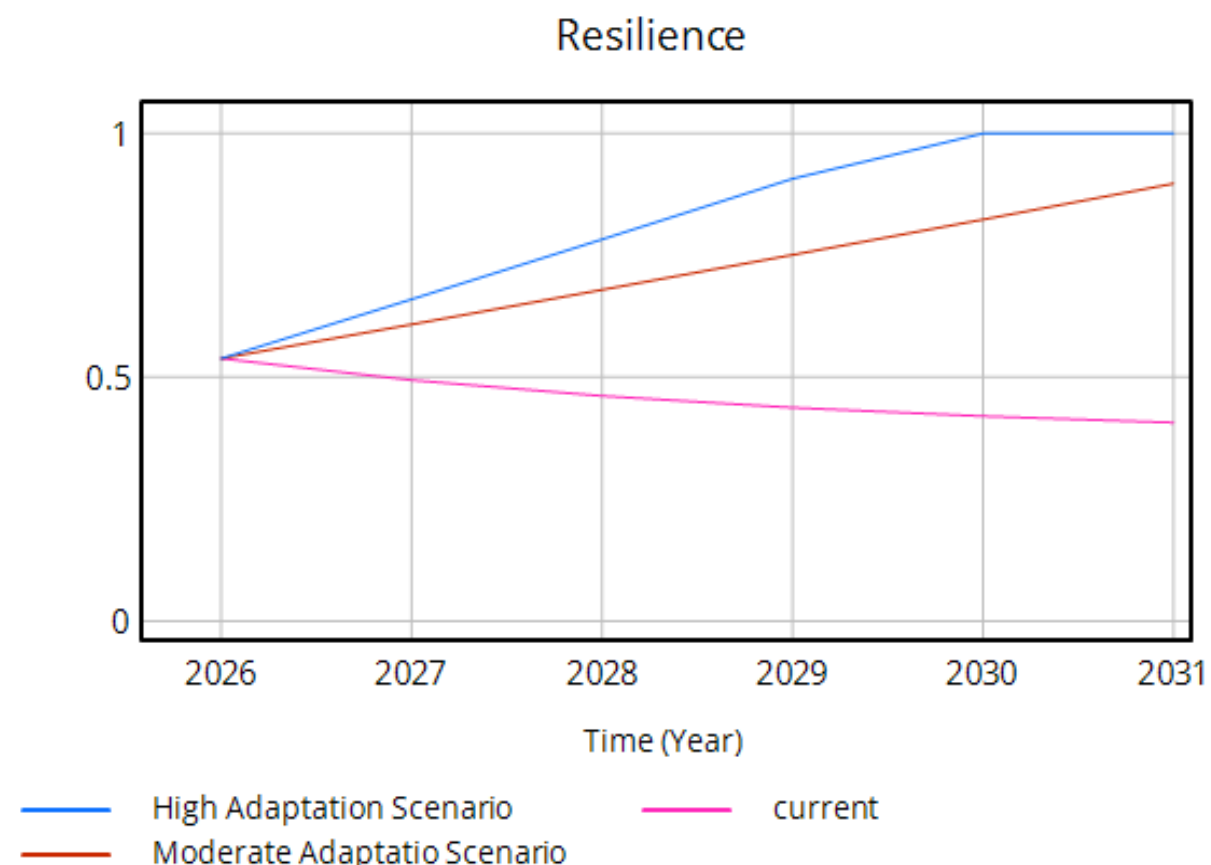


Figure 2. Comparison of Simulated Household Resilience Under Three Policy Scenarios (2026–2031).

The comparison of the three scenarios indicated different projected trajectories of household resilience. The Current Scenario showed a declining resilience index, whereas the Moderate and High Adaptation Scenarios produced increasing trajectories. The initial and final resilience values, together with their corresponding changes, are presented in Table 7.

Table 7. Changes in the Simulated Household Resilience Index Across Policy Scenarios (2026–2031)

Scenario	Resilience index (2026)	Resilience index (2031)	Change (index points)
Current	53.83	40.70	–13.13
Moderate adaptation	53.83	89.70	+35.87
High adaptation	53.83	100.00	+46.17

The simulation results suggest that different levels of adaptation intervention may generate substantially different household resilience trajectories. The Current Scenario produced a decline of 13.13 index points, whereas the Moderate and High Adaptation Scenarios generated increases of 35.87 and 46.17 index points, respectively. These differences highlight the potential importance of financial resources, institutional assistance, and adaptation capacity in shaping aquaculture household resilience within the simulated system.

Nevertheless, the results should be interpreted as model-dependent projections rather than definitive forecasts or empirical evidence of policy effectiveness. The magnitude and direction of the simulated changes depend on the model structure, parameterization, and assumptions underlying each scenario. Therefore, further model validation, sensitivity analysis, and empirical evaluation are necessary before these findings can support specific policy implementation decisions.

CONCLUSION

This study found that milkfish aquaculture households in Sibulue District, Bone Regency, exhibited a moderately resilient condition, with an overall resilience index of 53.87. The main areas requiring improvement included the adoption of adaptive technologies, livelihood diversification, and environmental management. The System Dynamics simulation indicated that household resilience, aquaculture production, income, and financial assets were projected to decline under the current scenario, whereas the moderate and high adaptation scenarios generated more favorable trajectories across these indicators. These findings highlight the potential importance of integrated adaptation strategies involving improved access to financial resources, government support, appropriate technologies, and capacity building for aquaculture households. However, the simulation outcomes represent exploratory, model-based projections dependent on the underlying assumptions and parameters rather than definitive predictions or empirically demonstrated policy effects. Further model validation and empirical assessment are necessary to strengthen the reliability of the findings and inform adaptation policies aimed at improving the long-term resilience and sustainability of milkfish aquaculture households.

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AUTHOR CONTRIBUTIONS

The authors declare that the contributions of each author to this work are as follows: RR as the corresponding author contributed to research design, data collection and analysis, system dynamics modeling, and manuscript preparation. SN contributed to conceptualization, analysis, and manuscript revision. AZ contributed to validation of the results and refinement of the manuscript. AM and RMM contributed to analysis system dynamic modelling.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest in the conduct of the research, data analysis, or preparation and publication of this article.

DECLARATION OF GENERATIVE AI

During the preparation of this manuscript, the author used chat GPT for the purpose improving language and clarity. All AI-assisted outputs were carefully reviewed, verified, and edited by the author. The author take full responsibility for the accuracy, integrity, originality, and content of the published article.

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