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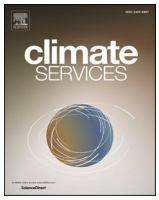

Hard and soft climate-smart investments in aquaculture in Bangladesh: Conditioning factors and decision space

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ABSTRACT

Climate change and its' associated weather variabilities and extremes are posing significant risks to aquaculture productivity, particularly in the coastal regions of Bangladesh. Concurrently, the increasing population and shifting consumption patterns are driving higher demand for aquacultural products. This study investigates the impact of floods, heavy rainfall, tidal surges, high temperatures, droughts, erratic rainfall, and water quality parameters (Dissolved Oxygen, ammonia, pH) on investments in "hard" assets, such as specific fish-farm equipment (aquaculture nets, fish cages, thermometers, irrigation pumps), to enhance climate resilience. Additionally, the study explores "soft" investments in information services that provide advanced forecasts on monsoon onset, heavy rainfall, dry spells, high temperature and cold spells. The results indicate that the level of investment in climate-smart aquaculture is currently influenced by climate stresses, investment capacity (farm size, family size), aquaculture system characteristics (pond size and depth, type of fish, aggregate yields), and market-related factors (proximity to roads and markets). In the context of climate-informed decision-making, forecast-based advisory services can facilitate the transition to climate-smart aquaculture. However, the benefits of the information services are often linked to substantial investments in hard infrastructure that ensure the effective utilization of climate information and advisory services. This absence of accessible climate information services and the capacity to invest in climate smart equipment that makes the information actionable, hinder the transition to climate smart aquaculture by smallholder farmers and hence threaten their livelihood and nutritional security.

1. Introduction

Aquaculture plays a crucial role in ensuring food and nutrition security, promoting gender equity, and reducing poverty in developing countries (Beveridge et al., 2013; Little et al., 2016, FAO, 2020). According to the FAO (2024), aquatic animal foods provide high-quality proteins – accounting for 15 percent of animal proteins and 6 percent of total proteins worldwide – and key nutrients including omega-3 fatty acids, minerals and vitamins. However, the global production of capture fisheries has plateaued at around 90 million tons annually over the past decade, putting pressure on the aquaculture industry to increase production to compensate for future shortages (Trinh et al., 2016). Furthermore, aquaculture needs to meet the protein demands of a rapidly growing global population, with current consumption levels at 80 g/day/person, while being inclusive of low-income groups (Ichien et al., 2016; Henchion et al., 2017). To ensure the food and nutrition security of the increasing population, it is estimated that fish production needs to increase by 37 % by 2030 and 85 % by 2050, with most of the increase expected to come from aquaculture (Troell et al., 2014). In the case of aquaculture production, it would need to increase from 83 million metric tonnes in 2018 to 131 million metric tonnes by 2050 to meet the demand (Boyd et al., 2022).

Bangladesh, a country where aquaculture plays a key role in the nutrition and wellbeing of farmers, is facing significant hydro-climatic challenges (Dastagir, 2015; Parvin et al., 2023) including variability in temperature and rainfall, and increased frequency and intensity of

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extreme climate events like droughts, floods, tidal surges, cyclones etc. (Daw et al., 2009; Kumar et al., 2021). These changes in climatic conditions have negative impacts on physiological (such as reproductive capacity) and ecological characteristics (i.e., distribution and migration patterns). and increasing mortality of economically important species in aquaculture. The increasing climate stress pose challenges for small-scale aquaculture farmers, industrial aquaculture and the global market for aquaculture products (Ichien et al., 2016; Mohanty et al., 2017; Abisha et al., 2022) To overcome these disruptive impacts in the business-as-usual scenario, a shift towards a climate-smart aquaculture approach is essential to increase production levels and meet the burgeoning demand (Nasr-Allah, 2019). The transition towards sustainable and climate-smart aquaculture practices can enhance the resilience of the growing aquaculture industry (Ichien et al., 2016, Yadav et al., 2024).

The concept of climate-smart aquaculture means production enhancement while adapting to climate stresses and mitigating the greenhouse gas emissions through investing in hard measures (infrastructural assets and input materials) and soft technical know-how (Parvaiz, 2024; Mohammed et al. 2021). Climate-smart aquaculture requires fish farming knowledge, skills and equipment to better adapt fish production to changing climate conditions (Colgan et al., 2019). In this article, the two groups of CSA technologies i.e. "hard" and "soft" technologies are discussed. Here the "hard" mainly refers to the physical/infrastructural assets including machinery, equipment and input materials that add climate resilience to aquaculture operations while the "soft" is the information and advisory services for timely operational actions with resilience benefits. There are also interdependencies between both kinds of technologies to be effective. The effectiveness of both hard and soft technologies is interdependent as information assists the best use of the material investments while information alone is often not useful in the absence of physical assets and/or input materials to apply the knowledge.

Aquaculture plays a key role in the economy of Bangladesh, which is valued at USD 3.6 billion and employs around 17 million people, or 11 % of the total population (Islam et al., 2024). In Bangladesh, fish accounts for two-thirds of the total animal protein consumption. Considering per capita daily intake, fish (62.6 g) is the third-most consumed food— after starches (471.3 g) and vegetables (167.3 g)— covering approximately 60 % of total annual animal protein intake (Rifat et al. 2023). Though the country is vulnerable to climate change, the coastal areas are disproportionately vulnerable due to the risk of floods, cyclones, and increasing salinity of both land and water (Hossain et al., 2018), which can undermine aquaculture production (Montes et al., 2022). To address this void, the current study focuses mainly on quantitative research conducted in four districts (with a larger area under aquaculture) viz. Barisal, Patuakhali, Khulna, and Sylhet in Bangladesh. The study investigates how farmers can modify their actions and decisions based on climatic forecasts (soft investment) and how exposure to repeated climate stress influences their investment in climate-smart aquaculture (hard investment). The main objective of this study is to analyze the decision-making process of aquaculture farmers in response to forecasted weather conditions and investment decisions in response to various climatic events such as delayed monsoon onset, heavy rainfall, dry spell, cold spell, and high temperature. Through this research, we aim to contribute to a better understanding of the actions and investments that can promote climate-smart aquaculture and ensure resilience and productivity despite the challenges of increasing climate stress in Bangladesh and beyond.

The use of climate-smart aquaculture (CSAq) innovations varies among the households (Le Quyen et al., 2019). The hypothesis put forward by the study is that the investment in CSAq depends on both household characteristics (age of household head, gender, aquaculture experience, education level, number of available laborers, farmers' knowledge about CSAq) and aquaculture characteristics (farm size, cooperative membership, aquaculture revenue) and exposure to extreme events. Aquatic food producers' ability to respond to climate risks requires enhanced capacity for modified management decisions (Dubey et al. 2017; Muthoka et al. 2024; Maulu et al. 2024), relying on climate information services (i.e., soft investment) with the support of context-specific assets/input materials (i.e., hard investments). The current research aims to add further understanding of the drivers of these investments.

2. Methods and sampling frame

The study on climate-smart aquaculture investment i.e. both soft (the decision support system) and hard investment (context-specific input materials and equipment) is based on data collected through face-to-face surveys. In total, 460 small-scale fish-farming households who are directly involved in fish-farming activities were surveyed using stratified random sampling from October 2019 to December 2019, which covered 18 unions (smallest administrative units) of the four selected upazilas from four districts. The districts (Barisal, Patuakhali, Khulna and Sylhet) were selected based on their contribution to aquaculture based fish production and exposure to climate risks while the four upazillas (Barisal Sadar, Patuakhali Sadar, Dacope and Sylhet Sadar) from these four districts respectively were selected within a 15–25 km radius of the Bangladesh-Meteorological Department's (BMD) weather stations. From each upazila, 115 small-scale fish-farming households who are involved in fish farming activity were randomly selected, which resulted 460 households and cover 18 unions (i.e., four from Barisal Sadar, four from Patuakhali Sadar, five from Dacope and five from Sylhet Sadar).

The basic information collected included the gender of the household head/respondent, family type (joint, nuclear) education levels (primary, secondary, college and above, no education). The farm household information collected are the total area of farmland, the total area of fishpond, the depth of the fishpond, types of ponds (perennial, seasonal), pond ownership (owned, leased), participation in fish farming training, distance to market, different types of fish farmed (Carps, Tilapia, Catfish, Bagda, Golda, Pangasius) along with responses to some follow-up questions. Other key information collected included the climate-smart aquaculture investments in fish-farm equipment such as aquaculture nets, pumps, thermometers, fish cages, aeration devices, and pH meters by farm households that can add resilience to aquaculture production despite the weather issues. The study further investigated the role of flood, heavy rainfall, high tidal surge, high temperature, drought, erratic rainfall, and water quality (Dissolved Oxygen, NH_3, pH) in the investment decision on specific fish-farm equipment. Aquaculture nets, and fish cages can be useful to protect fish from heavy rainfall, flooding, or tidal surge events while pumps, thermometers, aerators, and pH meters can be quite useful for water quality management during high temperature, drought, and erratic rainfall events (WorldFish, 2020; Hossain et al. 2021). The survey generated a dataset on the use of fish-farm equipment and exposure to weather factors as there is no current understanding of factors driving climate smart aquaculture investments. The study also performed a descriptive analysis of action points that can be taken by farmers given advanced forecasted information on monsoon onset, heavy rainfall, dry spell, high temperature, and cold spell.

2.1. Study area

Khulna, Barisal, and Patuakhali districts from the south-west coastal region and Sylhet from the north-east haor region were selected for this study (Fig. 1) considering their contribution to aquatic food production in Bangladesh (Kashem et al., 2017; DoF 2018; Shamsuzzaman et al., 2017) and at the same time their exposure to climate risks (Islam et al., 2019; Matin et al., 2016; Siddiqua et al., 2019). Moreover, aquaculture is a major source of animal protein, income, employment, and livelihood for rural communities and the economies of the selected four districts (DoF 2018; Hemal et al., 2017) indicating its' significant prospects for driving development and strengthening the rural economy.

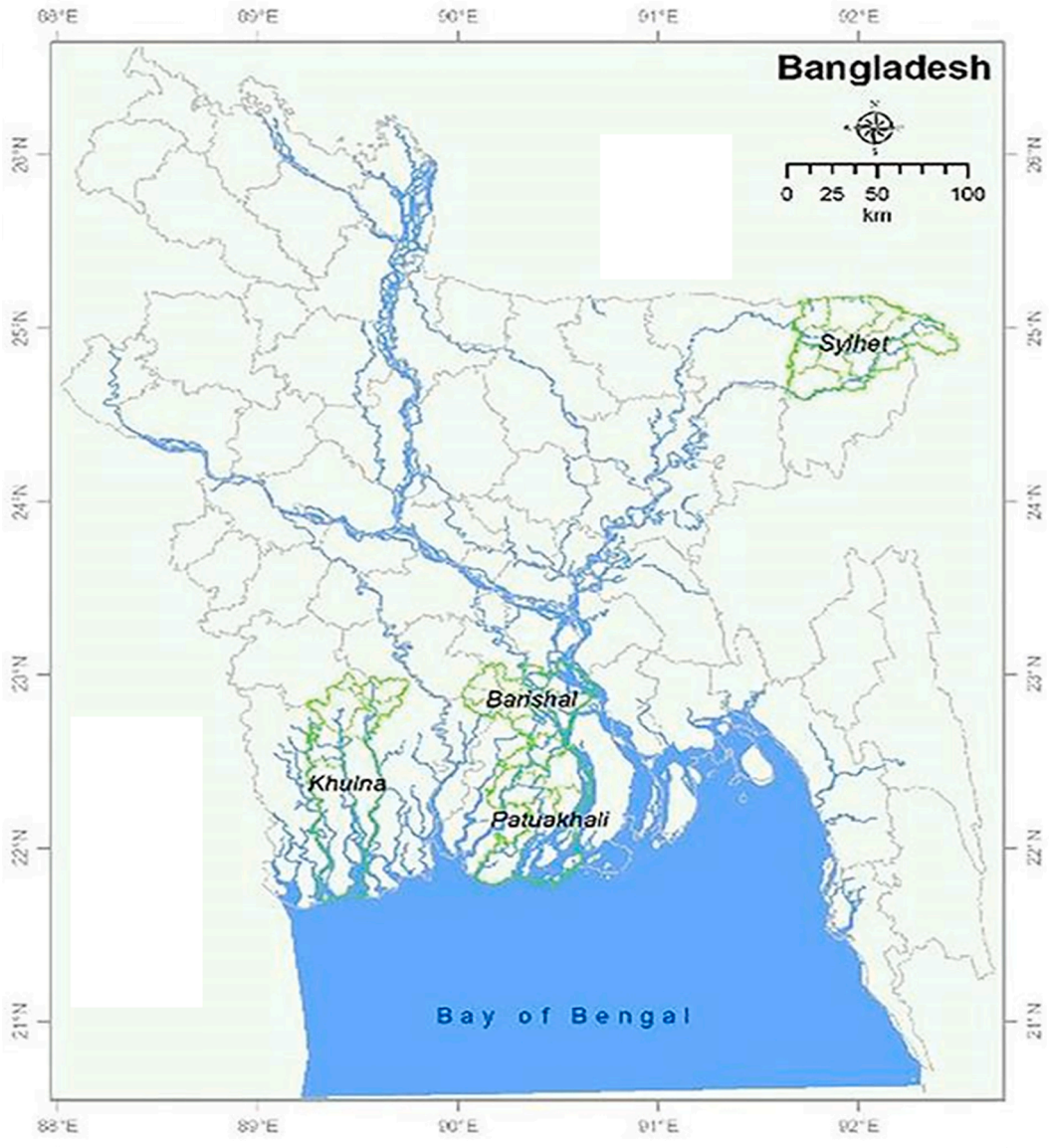

Fig. 1. Study districts (marked green). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.2. Logit Models on hard investment

The decision on climate-smart aquaculture investment by smallholder farmers is considered a dichotomous dependent variable measured as "yes" or "no". The logit model assesses the log odds of the dependent variable as a linear combination of independent variables. Investments considered here are aquaculture nets, fish cages, thermometers, and groundwater pumps. Though we considered aerators also, an inadequate number of farmers in the sample did not allow the model runs. If a farmer did not invest in a particular technology, the dependent variable is assigned a value of zero. The logit model is used to understand the linkage of the drivers of the technology especially the exposure to climatic risks. The probability of investment decision based on different climatic conditions is shown with the following the equation (Maddala, 1983):

$$f(x) = \frac{L}{1 + k(x - x_0)}$$

The logit model is used to model (Sheikh et al., 2003; Fecke et al., 2020; Adams et al., 2021; Giua et al., 2022) the probability of the farmer's use of fish farming equipment based on their exposure to different weather events and other factors related to farm, farmer, and market. For example, we use a logit regression model to understand whether a farmer will invest in an aquaculture fish net in response to an on exposure to high tidal surge. In case of soft investment on knowledge-intensive measures, we have analyzed the response rate on various actions farmers can adopt if they are receiving short-term weather forecasts. We used the software, STATA, for running the logit models.

3. Results

The following section 3.1 presents the logit model results on hard investments in relation to weather stresses and other independent variables while section 3.2 shows the descriptive analysis of the farmer-level measures (soft) that can be taken based on forecasted information.

3.1. Hard investments

The study investigated the influence of a portfolio of variables that can impact the decision to invest in climate smart technologies such as aquaculture nets, fish cages, thermometers and water pumps, The results of logit regressions showed that, among the climatic variables, heavy

rainfall is a significant driver for investment in aquaculture nets, fish cages (Table 1), thermometers and water pumps (Table 2). The high-temperature events are a significant driver for investment in thermometers and water pumps (Table 2). In case of high tidal surge, it leads to investments in , fish cages (Table 1), and thermometers (Table 2) while drought events lead to lower investment in aquaculture nets (Table 1) and increased investment in water pumps (Table 2). It is possible that dissolved oxygen (DO) levels also lead to investments in aerators, but the sample did not have sufficient number of farmers having aerators to conduct regressions. The water quality parameter of DO is relevant for investment in thermometers as temperature and DO levels are interconnected. These results implies that the weather extremes may trigger farmers to invest in equipment like thermometer, aquaculture nets, fish cages and water pumps to enhance their climate smartness.

In the case of household characteristics, the farmers' age and education are significant for aquaculture net investment, revealing that older and less educated farmers are using them. The training for fish farming is not significant for the investment in considered equipment, which may show the absence of relevant training content. Experience in aquaculture is significant for thermometer (Table 2) investment. None of the independent variables for household characteristics are significant for fish cages and pump investment, showing it is primarily driven by climate stress and market factors.

In the case of aquaculture characteristics (total farmland, area of fish pond, depth of fish pond, type of pond, pond ownership, farm distance from main road, farm distance from market, different fish types, total of

Table 1
Results of the logit regression on factors influencing investment in aquatic nets and fish cages by farmers in Bangladesh. (P value represents, *** $p < 0.01$, ** $p < 9.05$, * $p < 0.1$). **(Note: 1 decimal = 0.004 Hectare).**

	Aquaculture Net		Fish Cage	
	Coefficient	St. Error	Coefficient	St. Error
High tide surge# (yes −1/no −0)	0.00	0.42	2.72***	0.43
Drought# (yes −1/no −0)	−0.94***	0.35	2.05***	0.36
Monitoring Dissolved Oxygen# (yes −1/no −0)	−1.20	1.14	1.19	1.07
Monitoring Ammonia/$NH_3^{\#}$ (yes −1/no −0)	0.00	0.00	0.00	0.00
Heavy rainfall # (yes −1/no −0)	0.75**	0.30	0.98***	0.36
Monitoring pH# (yes −1/no −0)	0.00	0.00	0.00	0.00
Age of Farmer (years)	0.03**	0.01	0.02	0.01
Education of farmer (0-No education, 1-primary school, 2-secondary school, 3- college)	−0.31**	0.15	0.15	0.16
Gender (Female −1, else 0)	−0.21	0.68	−0.16	0.60
Marital status (Married −1, else 0)	0.72	0.63	−0.77	0.70
Adults in the family (>18 years) – number	−0.01	0.07	0.02	0.08
Family (joint) – (yes/no)	0.75**	0.32	−0.56	0.34
Total farmland (Owned) – Decimals (250 decimals is 1 ha)	0.00	0.00	0.00	0.00
Area of fish pond (Decimals)	0.00	0.00	0**	0.00
Depth of fish pond (Meter)	0-.33**	0.15	0.69***	0.26
Type of pond (Perennial −1, Seasonal-0)	0.66	0.41	2.2***	0.54
Pond ownership (Owned −1, Leased-0)	−0.01	0.42	0.18	0.43
Training fish farming (yes −1/no −0)	0.40	0.31	−0.39	0.30
Experience in aquaculture farming (years)	−0.15	0.17	−0.27	0.17
Farm distance (to main Road, Km)	−0.21	0.14	0.27*	0.14
Farm distance (to market, Km)	0.01	0.04	−0.09**	0.04
Carps (yes −1/no −0)	0.77	0.53	−1.24**	0.61
Tilapia (yes −1/no −0)	−0.15	0.36	−0.19	0.34
Catfishes (yes −1/no −0)	−0.77*	0.46	0.54	0.52
Bagda /freshwater prawn (yes −1/no −0)	−0.56	0.60	−0.50	0.55
Golda / saltwater shrimp (yes −1/no −0)	0.66	0.40	0.30	0.38
Pangasius (yes −1/no −0)	0.62*	0.37	0.78*	0.47
Total prawn & fish harvests (Kg)	0.0005**	0.00	0.00	0.00
Loan for fish farming (yes −1/no −0)	0.89	0.60	0.51	0.43
Constant	1.03	1.08	−1.62	1.22
Pseudo r-squared	0.21		0.28	
Chi-squared	114.59		161.10	
Number of observations	460		460	

Table 2
Results of the logit regression on factors influencing investment in thermometer and water pump by farmers in Bangladesh. (Number of observations, n = 460, P value represents, *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$).

	Thermometer		**Water Pumps**	
	Coefficient	St. Error	Coefficient	St. Error
High tide surge# (yes −1/no −0)	1.96***	0.58	−0.11	0.46
High Temperature (yes −1/no −0)	2.01***	0.49	3.18***	0.46
Drought# (yes −1/no −0)			2.46***	0.41
Erratic Rainfall (yes −1/no −0)	−0.60	1.24	0.48	0.57
Monitoring Dissolved Oxygen# (yes −1/no −0)	0.00	0.00	0.00	0.00
Monitoring Ammonia/$NH_3^{\#}$ (yes −1/no −0)	0.00	0.00	0.00	0.00
Heavy Rainfall (yes −1/no −0)	1.89***	0.73	1.19***	0.39
Monitoring pH (yes −1/no −0)	0.00	0.0.00	0.00	0.00
Age of Farmer (years)	0.00	0.02	0.00	0.01
Education of farmer (0-No education, 1-primary school, 2-secondary school, 3- college)	0.10	0.21	−0.21	0.16
Gender (Female −1, else 0)	0.00	.	0.94	0.74
Marital status (Married −1, else 0)	0.23	1.14	0.23	0.70
Adults in the family (>18 years) – number	0.12	0.11	−0.08	0.08
Family (joint) – (yes/no)	−1.1***	0.53	0.03	0.34
Total farmland (Owned) – Decimals (250 decimals is 1 ha)	0.00	0.00	0.00	0.00
Area of fish pond (Decimals)	0.00	0.00	0.00	0.00
Depth of fish pond (Meter)	−0.21	0.34	−0.41**	0.21
Type of pond (Perennial, Seasonal)	−0.33	0.55	−0.69	0.43
Pond ownership (Owned, Leased)	−0.49	0.55	0.42	0.45
Training fish farming (yes −1/no −0)	−0.27	0.43	0.17	0.31
Experience in aquaculture farming (years)	0.52**	0.26	0.30	0.19
Farm distance (to main Road, Km)	−0.08	0.20	0.02	0.16
Farm distance (to market, Km)	0.1***	0.04	−0.03	0.04
Carps (yes −1/no −0)	0.00	0.00	−1.2**	0.58
Tilapia (yes −1/no −0)	−1.58***	0.55	−1.4***	0.36
Catfishes (yes −1/no −0)	−0.11	0.75	−1.27**	0.55
Bagda /freshwater prawn (yes −1/no −0)	0.15	0.70	−0.74	0.61
Golda / salt water shrimp (yes −1/no −0)	−1.77***	0.62	−0.63	0.42
Pangasius	−1.31	0.85	0.00	0.39
Total prawn & fish harvests (Kg)	0,00***	0.00	0.00	0.00
Loan for fish farming (yes −1/no −0)	0.02	0.61	0.08	0.49
Constant	−3.27*	1.74	1.22	1.21
Pseudo r-squared	0.26		−0.08	0.08
Chi-squared	79.15		0.03	0.34
Number of observations	402		455	

prawn and fish harvest, loan taken for aquaculture farming), the total farmland is significant for pump investment (Table 2), the area of fish pond, depth of fish pond and type of pond is highly significant for fish cage investment (Table 1), while the farm distance from the road is significant for fish cage and pump investment, farm distance from the market is significant for fish cage (Table 1) and thermometer (Table 2) investment. The results also indicate that the investment for aquaculture net for tilapia and other catfishes is (Table 1) is significantly lower, Golda or freshwater prawn farmers are not investing in thermometers (Table 2), Aquaculture net and fish cage (Table 1) investments are significantly lower for Pangasius. The aggregate harvest of pond fish and prawn/shrimp is a significant factor for aquaculture net and pond thermometer investment.

3.2. Soft investments

In the case of knowledge-based soft investments, the operations farmers wanted to undertake based on forecasted information on monsoon onset, heavy rainfall, dry spells, high temperatures, and cold spells were collected and analysed. The operation that most farmers wanted to adopt for the monsoon forecast were fingerlings stocking, pond preparation and fingerlings collection. In fingerlings stocking operation, respondents of the Patuakhali district were highly responsive to monsoon onset information i.e. 60 % of the sampled farmers, where the Barisal, Khulna and Sylhet showed 55 %, 50 % and 40 % (Fig. 1a) response rate (willingness to modify the decisions based on the information). Sylhet farmers showed the highest response rate for pond preparation i.e., 65 % while the Patuakhali and Barisal farmers exhibited 50 % (Fig. 2a) rate of response. In addition, 50 % of respondents from Sylhet showed willingness to modify fingerlings collection activity. On the other hand, the least willingness was recorded in applying aqua-medicine (Fig. 1a), which needs to be done in accordance with many other factors.

With a heavy rainfall forecast, farmers were willing to adjust feeding, change fingerlings collection and stocking decisions, while having the least willingness to modify aqua-medicine application in all regions. In feeding adjustments, Sylhet showed a response rate of over 70 % where Patuakhali and Barisal farmers had 60 % and 50 % respectively. In fingerling collection, 65 % farmers from Khulna, and 50 % farmers from Sylhet wanted to use rainfall forecast for making decisions (Fig. 2b). Under dry spell forecast, the harvesting, feeding activities, and the pond preparation are the most potentially modified actions. 60 % of Patuakhali farmers wanted to change harvesting decision, while 55 % farmers in Sylhet wanted to change feeding decision. Majority of farmers in Khulna (70 %) wanted to change pond preparation activity if dry spell is forecasted (Fig. 2c). In high temperature forecasting, the aquaculture operations that farmers wanted to change were feeding, fingerlings stocking and fertilizer application. Farmers in Barisal showed high response rate of temperature forecast to feeding (80 %,), fingerlings stocking (80 %,) and fertilizer application (60 %) (Fig. 2d). Under cold spell forecasting, the farmers were interested in modifying harvesting, feeding and fertilizer applications. About 80 % of farmers in Khulna wanted to change harvesting decisions, 70 % of farmers of Sylhet intended to change feeding decisions and 58 % in Barisal district was interested to modify the fertilizer application (Fig. 2e).

4. Discussion and conclusions

According to the results of this study, climate stress is driving hard investments in fish-farm equipment such as aquaculture nets, water

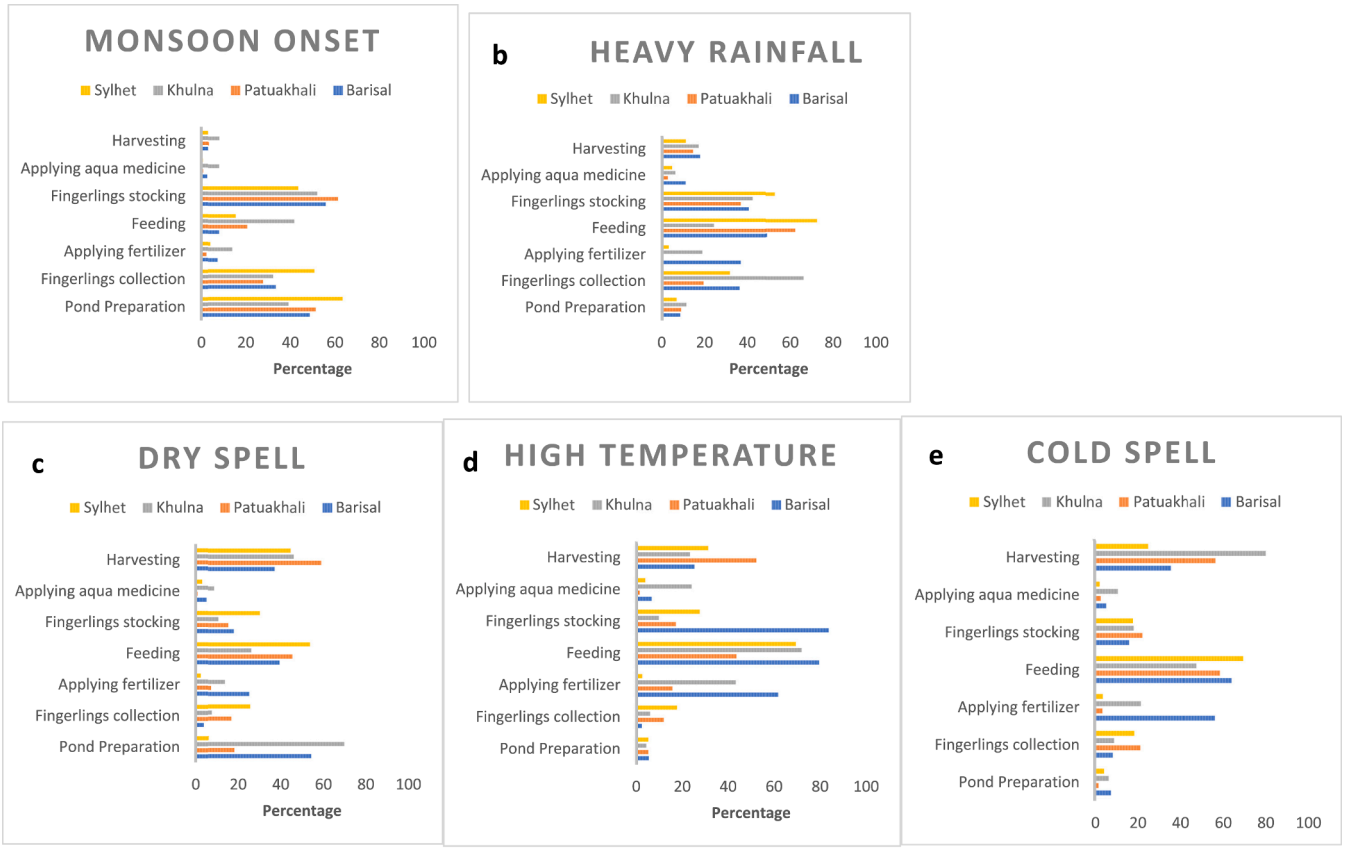

Fig. 2. Farmers willing to modify (Percentage) operations of harvesting, applying aqua medicine, fingerlings stocking, feeding, applying fertilizer, fingerlings collection and pond preparation using weather forecasts in four different districts viz. Barisal, Patuakhali, Khulna and Sylhet on Bangladesh (Alphabet a, b, c, d, e represents forecasts of monsoon onset, heavy rainfall, dry spell, high temperature, cold spell accordingly).

pumps, thermometers and fish cages. For instance, small scale fish-farmers in south-western part of Bangladesh, where temperature and rainfall variations, together with reduced freshwater influx during the dry season, result in seasonal salinization as well as extreme climatic events causing floods and waterlogging, have already started using cages to reduce fish loss (Uddin 2019) and nets to protect their ponds from loss and damage (Paul et al. 2024). The fish-farmers in the central and northern part particularly the Mymensingh and Cumilla region started using a wide range of aqua-medicines (Ahmed et al. 2015; Rahman et al. 2017) for water quality maintenance and to control disease outbreak, which are mainly due to temperature variation. Correspondingly, where rising temperature and drought are mostly affecting fish farming like in countries like Zambia, cage culture in natural lakes is also on rise (Hasimuna et al. 2019). Given the increasing weather variability and extremes due to climate change, these investments are expected to increase not only in Asia but also in Africa. However, these hard investments will also require soft investments in capacity building for small-scale fish farmers to help them decide which actions (using the machinery/equipment/inputs) should be taken in which context (Hossain et al., 2024; Resnick et al., 2024).

The results further clarified that the level of investment on climate smart aquaculture is currently determined by the exposure to climate stress, ability to invest (represented by farm size, family size), aquaculture system (pond size and depth, type of fish, aggregate yields), and market related factors (distance to road, distance to market) as well as socioeconomic factors (age and education of the farmer). The investment is also related to the aquaculture species cultivated. It can be understood that the training in fish farming and loan arrangement had no detectable influence on the investment yet. It highlights the need of policies oriented towards climate smart aquaculture, training and adaptation investment facilitation. The investment can also be targeted according to the stresses. In areas frequently affected with heavy rains, riverine and tidal flooding, investment in aquaculture nets and cage farming can be promoted. Based on forecasted information on very heavy rain, fish-farmers can prevent the fishes from escaping using such investments and prevent harvest losses (Hossain et al. 2021; Maulu et al., 2021). Besides, cage culture can be promoted for the flood prone regions to reduce the risks of flash floods during monsoon due to heavy rain (IGES, 2009, Parvez, 2018). This could potentially reduce the loss of fishes due to such stresses. The areas with frequent drought and high temperature can invest in thermometer and water pumps. Using thermometers, fish-farmers can check the water temperatures to decide the application of lime for controlling water pH, or to use aerators for balanced dissolved oxygen level and to modify feed management for reduced mortality rate (Hossain et al. 2021; WorldFish, 2020). Decision on using irrigation pumps for maintaining pond water-level during dry spell can also substantially reduce the risks or mortality and disease outbreak and enhance sustainable production. The investment on pumps is also related to farm size, which shows the multi-purpose nature of this investment, especially for irrigating ponds. Temperature stress is also related to dissolved oxygen, which shows an increased investment in water pumps. This could potentially be applicable to aerators also but the limited number of aerators in the sample did not allow quantitative estimation. However, this limited number of aerators indicates the limited capacity of small-scale fish-farmers in terms of hard investment to manage the associated climate risks. The future intensity and frequency trend in temperature, rainfall, drought and flood events point towards the need to accelerate hard investments for climate smart aquaculture and technology based training for small-scale fish-farmers.

In terms of soft investments for actionable information, both short term (5 day or weekly) and seasonal forecasts are critical to reduce climate risks. It is mainly so, as the short-term forecasts can be used in day to day aquaculture management decisions to reduce associated day to day climate risks (Hossain et al. 2021). On the other hand, seasonal forecasts can provide information on upcoming climatic conditions for over a season which can be used by the aquatic food producers to plan for forthcoming seasonal aquaculture operations to manage climate risks (Carlo et al. 2022); particularly when climate variability exceeds the suitable range, even if there is no long-term trend (Hobday et al. 2018). For instance, depending on the information from seasonal forecasts, fish-farmers can decide a particular period for pond preparation, fingerling stocking, adjusting production volume, adjusting maintenance schedule, and harvesting schedule. These climate sensitive management decisions are very much crucial for aquaculture operations in managing climate risks, reducing costs, and ensuring business profit. Hard investments in aquaculture equipment make the weather information to be valuable by ensuring the ability to take right action (eg: use of aerators at extreme temperature or aquaculture nets for extreme rainfall) at right time and hence building a climate resilient aquaculture production system.

As per the study, it is clear that forecasts-based advisory can be used by aquaculture farmers for their decision-making process. Farmers prefer to use dry spell, cold spell, and high temperature information for feeding and harvesting operations. The research findings indicate that the onset of monsoon and heavy rainfall information plays a critical role in fingerling management, as it enables farmers to optimize their production. Furthermore, the onset of monsoon and dry spell information is relevant for pond preparation, as it allows farmers to prepare their ponds adequately for optimal fish growth. The study also found that heavy rainfall and high temperature information are significant in determining the appropriate timing for fertilizer application. It further indicated that most of the information gathered is not currently useful for disease management and aqua-medicine use. Hence, further research is required for forecast-based weather information for fish disease management. In aquaculture, the use of weather forecasts and warning of the abnormal aquaculture environmental parameters are useful for farmers (Hu et al. 2020). Access to financial services in favourable terms and conditions from Banks or finance institutions is required for investments such as irrigation pumps, aerator, nets, fish cages and any other infrastructural investment to deal with the climate variability induced risks. Given the fact that banks ae reluctant to lend to aquaculture farmers in Bangladesh, climate smart aquaculture will be challenging for smallholder farmers to achieve. If 10 percent of the loss and damage to aquaculture in Bangladesh can be offset by appropriate climate information services and decision enabling equipment, its economic value can be around USD 14 million a year (Shammunul et al. 2024). ClS can assist in both operational and strategic decision making for on-firm aquaculture operations to manage climate risks (Hossain et al. 2024), however, the potential of CIS is yet to get realized (Yuwan et al. 2024). Although it might take years to reach the desired level of investment, govt. needs to understand the synergy of both hard and soft investments in aquaculture in order to have a comprehensive policy towards climate smart aquaculture research and development as well as finance (Pedersen et al., 2024).

CRediT authorship contribution statement

T.S. Amjath-Babu: Writing – original draft, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Peerzadi Rumana Hossain:** Writing – original draft, Project administration, Investigation, Data curation, Conceptualization. **Sanzida Akhter Anee:** Writing – original draft, Visualization. **Essam Yassin Mohammed:** Writing – original draft, Validation. **Timothy J. Krupnik:** Writing – review & editing, Supervision.

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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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Data availability

Data will be made available on request.

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