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ORIGINAL ARTICLE

Does climate change matter for freshwater aquaculture in Bangladesh?

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Abstract Freshwater aquaculture plays an important role in the economy of Bangladesh, providing food, income, livelihoods and export earnings. However, freshwater aquaculture in the Mymensingh area of north-central Bangladesh has been accompanied by recent concerns over climate change. Field survey revealed that different climatic variables including flood, drought, rainfall variation and temperature fluctuation have had adverse effects on pond-fish culture. These climatic variables have detrimental effects on the ecosystem of ponds and thus affect survival, growth and production of fish. Changes in climatic variables have adverse effects on fish reproduction, grow-out operation, parasite infestation and disease occurrence. Considering vulnerability to the effects of climate change on pond-fish culture, we propose adaptation strategies that need to be introduced to cope with the challenges.

Keywords Fish culture · Pond ecosystem · Climatic variables · Vulnerability · Adaptation

Introduction

Aquaculture is one of the fastest growing food production systems in the world as the sector has expanded at an average annual rate of 8.6 % over the last three decades (1980–2012). Global fish production reached 66.6 million tons in 2012 of which Asia accounted for 88.4 %. Bangladesh is ranked fifth in global aquaculture production after China, India, Vietnam and Indonesia (FAO 2014). Bangladesh is one of the most suitable countries in the world for freshwater aquaculture, because of its favourable biophysical resources and agro-climatic conditions. The total annual fish production in Bangladesh was estimated at 3.41 million tons in 2012–2013,[1] of which 1.86 million tons (55 %) were obtained from inland aquaculture, 0.96 million tons (28 %) from inland capture fisheries and 0.59 million tons (17 %) from marine fisheries (FRSS 2014). The total annual fish production has gradually increased from 1.99 million tons in 2002–2003 to 3.41 million tons in 2012–2013, an average annual growth rate of 7.14 % over the last decade. About 782,559 ha of closed-water bodies are currently operated for aquaculture by 14.69 million farmers (DoF 2014). Fish culture in ponds[2] is the main freshwater aquaculture practice in Bangladesh.

Freshwater aquaculture plays an important role in the economy of Bangladesh, providing food, income, livelihoods and export earnings. Fish contributes 60 % of national animal protein consumption. Moreover, fish accounts for 4.37 % of gross domestic product (GDP), 23.37 % of agricultural GDP and 2.01 % of export earnings (DoF 2014). In 2012–2013, Bangladesh exported 43,953 tons of freshwater prawn and marine shrimp valued at US$396 million, of which US$92 million (23 %) was prawn (FRSS 2014).

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[1] Bangladesh fiscal year: 1 July–30 June.

[2] Freshwater aquaculture in Bangladesh can be divided into: (1) pond-fish culture, (2) rice-fish farming, (3) cage culture and (4) floodplain aquaculture. This article deals with pond-fish culture which is dominant among farming systems.

However, while freshwater aquaculture in Bangladesh provides huge benefits, pond-fish culture has been accompanied by recent concerns over climate change. A number of climate-related threats to freshwater aquaculture have been identified (Brander 2007; De Silva and Soto 2009). Climate change is projected to impact largely across ecosystems and economies in the aquaculture sector (Holmyard 2014). The potential impacts of climate change on freshwater aquaculture could have severe consequences for the economy of Bangladesh. Although coastal aquaculture is more vulnerable than inland (Ahmed and Diana 2015a), future climate change will severely affect fish production. The vulnerability of fishery-based livelihoods to the impacts of climate change has recently increased (Islam et al. 2014). High population density, poor socioeconomic conditions and low adaptive capacity have made the population of Bangladesh highly vulnerable to climate change (Shahid et al. 2015).

Considering vulnerability to the effects of climate change on freshwater aquaculture, adaptation strategies must be developed to cope with the challenges. It is likely that reducing the impacts of climate change on pond-fish culture will require a combination of adaptation strategies and policies (Shelton 2014). Addressing potential adaptation options and mitigation measures would help to increase resilience to climate change in aquaculture (De Silva and Soto 2009).

The aim of this paper is to assess the potential impacts of climate change on pond-fish culture in rural Bangladesh. It also examines ecological effects of climate change and their consequences on fish production. Finally, we set out some preliminary conclusions about the adaptation of freshwater aquaculture to climate change.

Climate change and Bangladesh

Bangladesh is one of the most disaster-prone countries in the world because of its geographical location. According to the Global Climate Risk Index, Bangladesh is ranked sixth among countries vulnerable to climate change, while it was ranked first in 2012 (Harmeling and Eckstein 2012; Kreft et al. 2014). Bangladesh is vulnerable to a combination of climatic variables, including cyclone, drought, flood, rainfall, salinity and sea level rise.

Coastal Bangladesh is prone to cyclones. Between 1877 and 1995, Bangladesh was hit by 154 cyclones, including 43 severe cyclones (Dasgupta et al. 2014). On average, a severe cyclone hits Bangladesh every 3 years (GoB 2009). A cyclone in 1970 and 1991 resulted in the death of around 300,000 and 138,000 people, respectively. In November 2007, cyclone Sidr slammed coastal Bangladesh with economic losses of US$1.6 billion (DMB 2010). In recent years, cyclone Aila, Bijli, Giri, Mahasen and Nargis devastated coastal life in Bangladesh. It seems that the intensity of cyclones may increase by 5–10 % (FPMU 2013).

Drought in Bangladesh can be categorised into agricultural, hydrological, meteorological, seasonal and socioeconomic drought (Ramamasy and Baas 2007). During the last 50 years, Bangladesh experienced 19 droughts (Habiba et al. 2012). The frequency of droughts in Bangladesh has recently increased due to global warming and lack of rainfall. An El Niño[3] event with global warming in the central Pacific Ocean can cause the Indian monsoon to switch into a dry mode, resulting significant reductions in rainfall leading to droughts (Conway and Waage 2010). In Bangladesh, drought-affected area in the dry season could increase from 4000 to 12,000 km^2 (FPMU 2013).

Bangladesh is a flood-prone country, and 20 % of the country is normally flooded each year. Bangladesh experienced five extreme floods between 1987 and 2007 (Mirza 2011). Rainfall, river discharge and tidal surges increase floods. Bangladesh has no control over river flooding as the country has around 700 rivers[4] including 57 trans-boundary rivers. About 1.7 million ha of floodplains are prone to river erosion (Alam and Ahmed 2010). Around 14.6 million people in coastal Bangladesh are vulnerable to inundation, and this number will increase to 18.5 million by 2050 (World Bank 2012).

Bangladesh falls in the region of huge rainfall as the country is situated in the monsoon belt with the Himalayas in the north and the Bay of Bengal in the south. Annual rainfall in Bangladesh varies from 1400 to 4300 mm, and the average annual rainfall increased at a rate of 5.52 mm between 1958 and 2007 (Shahid 2010). Monsoon rainfall in Bangladesh is predicted to increase 10–15 % by 2030 (FPMU 2013). There is a direct influence of global warming on changes in rainfall patterns as the water holding capacity of air increases 6–7 % for every 1 °C increase in temperature (Trenberth 2005).

Saltwater intrusion is an increasing problem in Bangladesh. Saltwater from the Bay of Bengal has reached over 100 km inland (DMB 2010). Cyclones with tidal surges, sea level rise and upstream withdrawal of freshwater are likely to play a critical role in increasing salinity. Salinity has recently increased in coastal rivers to 4 ppt in the monsoon and 13 ppt in the dry season (Khan et al. 2011). About 1.06 million ha of land in coastal Bangladesh have been affected by salinity (FPMU 2013), which is predicted to increase two million ha by 2050 (Conway and Waage 2010).

[3] El Niño is the warm phase of the El Niño Southern Oscillation, refers to the cycle of warm temperatures that occurs across the tropical Pacific Ocean.

[4] Bangladesh is often called a "land of rivers".

Bangladesh is vulnerable to sea level rise as the country lies just less than 2 m above sea level (Schiermeier 2014). Sea level is rising by 15.9–17.2 mm each year in Bangladesh (Pethick and Orford 2013), while global sea level rises 2–3 mm each year (Schiermeier 2014). A 45-cm rise in sea level would inundate 11 % of Bangladesh that will make millions of people homeless, and they will become "climate refugees" (Mirza 2011). Sea level could rise 1 m by 2100 (Rahmstorf 2007), and such a rise would largely affect the Sundarbans[5] mangrove forest. Sea level rise is predicted to inundate 120,000 km^2 of Bangladesh (FPMU 2013).

Methodology

Study area

The study was undertaken in the Trishal sub-district under Mymensingh district of north-central Bangladesh (Fig. 1). Geographically, Mymensingh has been identified as the most important area for aquaculture because of the availability of ponds, warm climate and fertile soil. Mymensingh is known as the "hub of freshwater aquaculture" in Bangladesh. Rapid development of aquaculture in Mymensingh has been linked to a "blue revolution" (Ahmed 2009; Ahmed and Toufique 2015). Small-scale aquaculture has benefited, especially from sustained efforts in a long-running development project (1989–2003), namely the Mymensingh Aquaculture Extension Project. The development of private hatcheries and feed industries has also supported an expanding aquaculture industry in Mymensingh.

Mymensingh is ranked first among districts of pond-fish production in Bangladesh. In 2012–2013, the total annual pond-fish production in Mymensingh was 270,437 tons from 27,123 ha area, an average annual production of 9.97 tons/ha compared to 3.90 tons/ha in national average (FRSS 2014). Carp polyculture is a traditional practice in Mymensingh and farmers commonly stock a combination of Indian major carp and exotic carp. In recent years, a number of farmers practice catfish and tilapia farming. Although most farmers are involved in extensive and improved-extensive farming, an increasing number of farmers are using semi-intensive methods.

Data collection methods

Field research was conducted for 6 months from July to December 2013. A combination of participatory, quantitative and qualitative methods was used for primary data collection, including (1) questionnaire interviews, (2) focus group discussions (FGD) and (3) key informant interviews. Multi-method approaches were used for triangulation in data collection. Triangulation is a technique that facilitates validation of data by using two or more data collection methods. Using triangulation as a methodological metaphor can facilitate the integration of quantitative and qualitative results that help researchers to clarify their theoretical plans and the basis of their findings. The integration of quantitative and qualitative approaches is increasingly recognised because of better understanding empirical research results (Östlund et al. 2011).

Questionnaire interviews with fish farmers were preceded by preparation of a survey and pilot testing of the interview schedule. For questionnaire interviews, farmers were selected through stratified random sampling of the following culture species and farming systems: (1) carp polyculture, (2) pangas monoculture and (3) tilapia farming. A total of 150 fish farmers, 50 in each culture system, were interviewed in their homes or at pond sites. Several visits were made to selected farms to observe farming practices. The interviews, which lasted about an hour on average, focused on perceived impacts of climate change on pond-fish culture. In order to assess the impacts of climate change on pond-fish culture, relative rank was applied for climatic variables. The ranking scale was between 1 and 5, where 1 = not vulnerable, 2 = less vulnerable, 3 = moderate vulnerable, 4 = highly vulnerable and 5 = extremely vulnerable.

FGD were conducted with fish farmers, hatchery operators and community members to obtain information regarding the impacts of climate change on aquaculture. The advantage of FGD over other methods is that it allows wider participation of the community, and therefore the information collected is likely to be reliable. A total of 15 FGD sessions were conducted and each group consisted of 6–15 people, thereby allowing a total of 153 participants. The FGD sessions, which lasted up to 2 h, were held in front of village shops, under large trees and in farmers' houses.

Validation of the information collected was undertaken through cross-check interviews with key informants. A key informant is someone with special knowledge about the impacts of climate change on aquaculture. Cross-check interviews were conducted with government fisheries officers, researchers, policymakers and development workers. Key informants provided expert opinions on climate change in the context of pond-fish culture. They also provided suggestions regarding adaptation strategies in relation to climate change, based on their knowledge and experience. A total of 30 key informants were interviewed in their offices or work locations.

[5] The Sundarbans is the largest mangrove forest in the world, located along the mouth of the Bay of Bengal between Bangladesh and India.

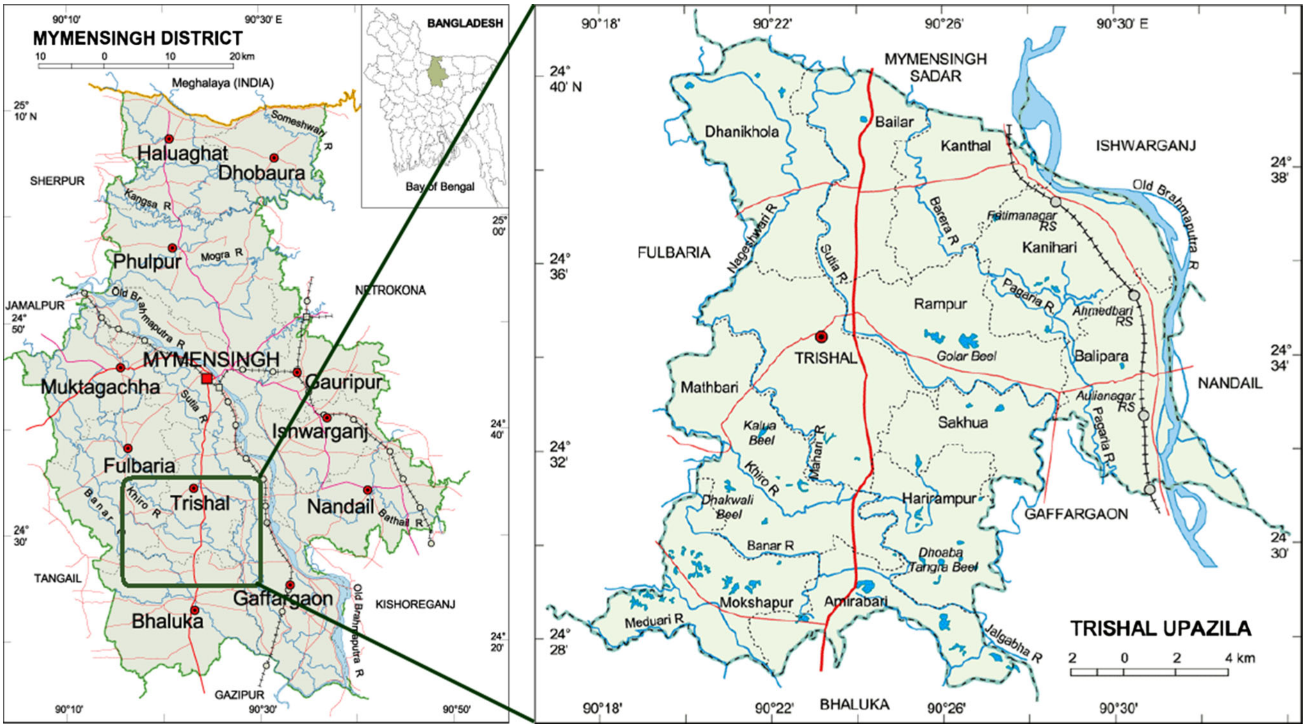

Fig. 1 Map of Mymensingh district in Bangladesh, showing the study area of Trishal

Data analysis

Data from questionnaire interviews were coded and entered into a spreadsheet using Microsoft Excel to produce descriptive statistics. The distribution of ranks to evaluate the impacts of climate change on fish culture was assessed using Kendall's coefficient of concordance, also known as Kendall's *W*. The measure of Kendall's *W* range from 0 to 1 and guidelines for interpreting Kendall's *W* values are: (1) $W = 0.1$, agreement: very weak, confidence: none; (2) $W = 0.3$, agreement: weak, confidence: low; (3) $W = 0.5$, agreement: moderate, confidence: fair; (4) $W = 0.7$, agreement: strong, confidence: high and (5) $W = 0.9$, agreement: usually strong, confidence: very high (Schmidt 1997). Moreover, content analysis method was used for qualitative data. Results from the data analysis were used to describe the impacts of climate change on pond-fish culture.

Results and discussion

Climatic variables for freshwater aquaculture

According to the survey, four climatic variables were identified those have adverse effects on pond-fish culture in the study area: (1) flood, (2) drought, (3) rainfall variation and (4) temperature fluctuation.[6] Mean ordinal rank indicated that flood was the most significant climatic variable that affected pond-fish culture, followed by drought, rainfall variation and temperature fluctuation (Table 1). Almost all surveyed farmers expressed concern over fish culture due to the effects of these climatic variables. Kendall's *W* value was slightly higher for carp (0.62) than tilapia (0.55) and pangas (0.53) culture, suggesting that carp farming is more susceptible to climate change than other farming systems.

Flood

Floods are becoming more frequent in fish farming communities in the study area. According to farmers, unusual flooding has increased dramatically in recent years. Heavy monsoon rainfall directly causes greater frequency of floods during the peak season of aquaculture. Pond-fish culture is extremely vulnerable to flooding. Farmers perceived that floods are the most significant threats to loss of total harvest as sudden or prolonged floods often cause physical damage to ponds. Preventing escape of fish is very difficult during floods as farmers are unable to raise their low and narrow dikes. Emergency harvesting of fish during floods cannot compensate for the economic loss because of

[6] Other climatic variables, including cyclone, salinity and sea level rise affect coastal aquaculture (Ahmed and Diana 2015b).

Table 1 Ranking of farmers' opinions for the effects of climatic variables on pond-fish culture

Climatic variable	Farming system									Mean ordinal rank[b]
	Carp ($n = 50$)[a]			Pangas ($n = 50$)[a]			Tilapia ($n = 50$)[a]			
	Score mean ± SD	*W* value	Chi-square (χ^2) value	Score mean ± SD	*W* value	Chi-square (χ^2) value	Score mean ± SD	*W* value	Chi-square (χ^2) value	
Flood	4.70 ± 0.61			4.66 ± 0.63			4.68 ± 0.55			1
Drought	4.66 ± 0.74	0.62	120.67	4.62 ± 0.75	0.53	104.54	4.64 ± 0.72	0.55	107.54	2
Rainfall	3.40 ± 0.97		$P < 0.0001$	3.32 ± 0.87		$P < 0.0001$	3.36 ± 0.85		$P < 0.0001$	3
Temperature	3.22 ± 0.68			3.14 ± 0.70			3.18 ± 0.69			4

[a] *n* number of farmers

[b] Based on mean scores of all farming systems

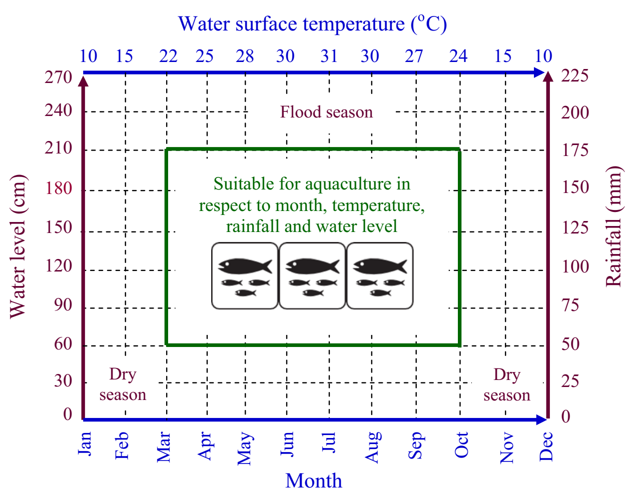

Fig. 2 Schematic diagram of a pond showing conditions suitable for fish culture in relation to climatic variables; *vertical lines* show relationship between month and average daytime water temperature; similarly *horizontal lines* show relationship between water level and average daily rainfall; flood and dry season are related to month, water level, temperature and rainfall (based on field assessment)

limited ability to market the crop during floods. Bangladesh lost 1.2 million tons of crop production by flood in 2007 with economic losses of US$1.4 billion (Mirza 2011). Poor fish farming communities are particularly vulnerable to inundation by floods which often destroy their homes. Small-scale farmers cannot invest in aquaculture after floods because of cost associated with house construction.

Drought

Field survey revealed that drought in the dry season from November to February is one of the foremost environmental limits to pond-fish culture (Fig. 2). Seasonal drought causes poor access to water in ponds. Reducing groundwater levels is also concerned for water shortage in ponds. Groundwater level in northern Bangladesh declined from 3.7 m in 1981 to 6.6 m in 2011 (FPMU 2013). According to farmers, severe or prolonged droughts often result in short culture period for fish. Year-round fish culture is not possible due to scarcity of water. Most ponds dry up during the dry season causing unfavourable conditions for fish, and thus fish become more crowded and stressed in low volume of water. Drought also affects pond-dike cropping. Most surveyed farmers (78 %) reported that drought reduced fish consumption because of low production. Moreover, fish prices increased during drought due to limited supply to markets. According to key informants, droughts have reduced the coping mechanisms of food insecurity by fish farming households. Surviving drought has always been hard as severe droughts often cause food shortage in fish farming communities. Food production in Bangladesh might be reduced 30 % by 2100 due to climate change (FPMU 2013).

Rainfall variation

Rainfall variability has increased the risk of flood and drought in the study area. Field survey revealed that 80 % of the rainfall occurs between March and October, ranging from 50 to 175 mm/day that suitable for fish farming (Fig. 2). Early or late rainfall with increased incidence of sudden heavy rain has occurred in fish farming communities. The average annual pre-monsoon rainfall in Bangladesh increased at a rate of 2.47 mm between 1958 and 2007 (Shahid 2010). According to farmers, heavy rainfall often wreaks havoc on fish production. Changes in the rainy season with storm weather pattern have severely affected aquaculture. Intense rainfall causes physical damage to pond-dikes and farmers lose their crops as fish crawl over dikes during heavy rain. Fish marketing is also a problem during rainy days because of poor road and transport facilities in remote farming communities, and delay in marketing which in turn affects the quality of fish. Human mobility for economic activities and social interactions is largely affected by heavy rainfall as fish farming households could not move during rainy days. Moreover, extreme rainfall often leads to mudslides and destroys household assets in fish farming communities.

Temperature fluctuation

Water temperatures in fish ponds have become more variable in recent years. Field survey revealed that lower water temperatures in the winter season have increased the number of cold days. Long-lasting cold weather has also reduced fish culture period. Pond water temperature in the winter season drops below 15 °C, which is too low to support fish production. Conversely, farmers reported that summer water temperatures in ponds may have increased 1–2 °C. It is predicted that average temperature in Bangladesh is likely to increase 1.4 °C by 2050 and 2.4 °C by 2100 (Shahid 2012). A 2 °C increase in temperature could increase 29 % of flooded area in Bangladesh (Mirza 2011). According to key informants, increased water temperature above optimal (22–30 °C) has an adverse impact on fish production. Fish are very sensitive to water temperature and small increases (1–2 °C) in temperature may have sub-lethal effects on tropical fish (Ficke et al. 2007). Increase in water temperatures have resulted in longer hot seasons. Dangerously hot weather has already occurred more frequently in summer. Because of increased temperatures and heat waves, farmers reduced working hours in fish culture during summer.

Effects on pond ecosystem

Fish are highly sensitive to ecological conditions, and changes in pond ecosystem have severe effects on their survival, growth, feeding and production (Fig. 3). Field survey revealed that water quality of fish ponds is highly affected by flooding due to contamination with pollutants from land-based sources. During field visits, floodwater was observed to increase the sedimentation of ponds and might reduce photosynthesis, resulting in lower levels of dissolved oxygen (Tucker and Hargreaves 2004). Fish have high oxygen demand, and the reduction of oxygen below 5 ppm is likely to increase fish mortality (Jadhav 2008). According to key informants, rapid oxygen depletion can result in declining pond productivity. Overall, floodwater poses an additional threat to the pond ecosystem, leading to hinder ecological interactions among biotic and abiotic components, resulting in an overall loss of fish production.

Drought has severe consequences for the ecosystem of fish ponds as drought reduces water levels and changes water quality. Farmers reported that deteriorating water quality and decreased water levels in ponds have reduced fish habitat. According to key informants, drought increased the concentration of waste metabolites (ammonia, carbon dioxide and nitrites) that can alter the ecosystem of ponds, and thus affect growth and production of fish. Drought also reduces water circulation and primary productivity in ponds. Reduction in primary productivity caused by drought could turn temperate ecosystems into carbon sources (Ciais et al. 2005). A major drought effect is the reduction of photosynthesis that can have impacts on carbon balance in ecosystem (Rocha and Goulden 2010).

The impacts of rainfall variation on the ecosystem of fish ponds are becoming increasingly apparent. Heavy rainfall has increased water depth of ponds that may affect ecosystem. During field visits, it was observed that a huge volume of debris and trash washed into ponds by rainwater, causing water turbidity. Turbid water reduces sunlight penetration into ponds that inhibits oxygen production by reducing photosynthesis and limits plankton availability (Tucker and Hargreaves 2004). Intense rainfall can cause lower water pH in ponds that may have adverse ecological effects as pH ranging from 7.5 to 9 (alkaline) is suitable for fish production (Jadhav 2008). Eventually, ecological changes in ponds by rainfall variation have effects on growth and production of fish.

Changes in water temperature may provoke multiple effects on pond ecosystem. According to key informants, increased water temperature may increase toxicity of ponds that may reduce oxygen level. A combination of higher water temperature and lower dissolved oxygen may provoke lower fish production (Jeppesen et al. 2010). Key informants reported that changes in water temperature of ponds often cause stratification and less nutrient enrichment to surface waters. Increased stratification of water is likely to lead to changes in food web (Ficke et al. 2007; Barange and Perry 2009). Increased water temperature exacerbates the occurrence of algal blooms (De Silva and Soto 2009), and fish mortalities occur during summer in relation to harmful algal blooms (Rodgers 2008).

Impacts on fish reproduction and grow-out operation

Fish reproduction and hatchery operation

Field survey revealed that long hours of daylight with favourable temperature (25–30 °C) from March to September are suitable for fish hatchery operation. However, changes in climatic variables have detrimental effects on fish reproduction and hatchery operation, resulting in an overall loss of quality fry production. The price of fry with supply and demand varies greatly due to impacts of climatic variables on hatchery operation (Table 2).

Hatchery operators reported that flood has dramatic effects on broodstock ponds as a result of siltation and water pollution. Similarly, water quality of broodstock ponds is seriously affected by drought. Deteriorating water quality in broodstock ponds has severe effects on fish reproduction. Field survey revealed that rainfall variation

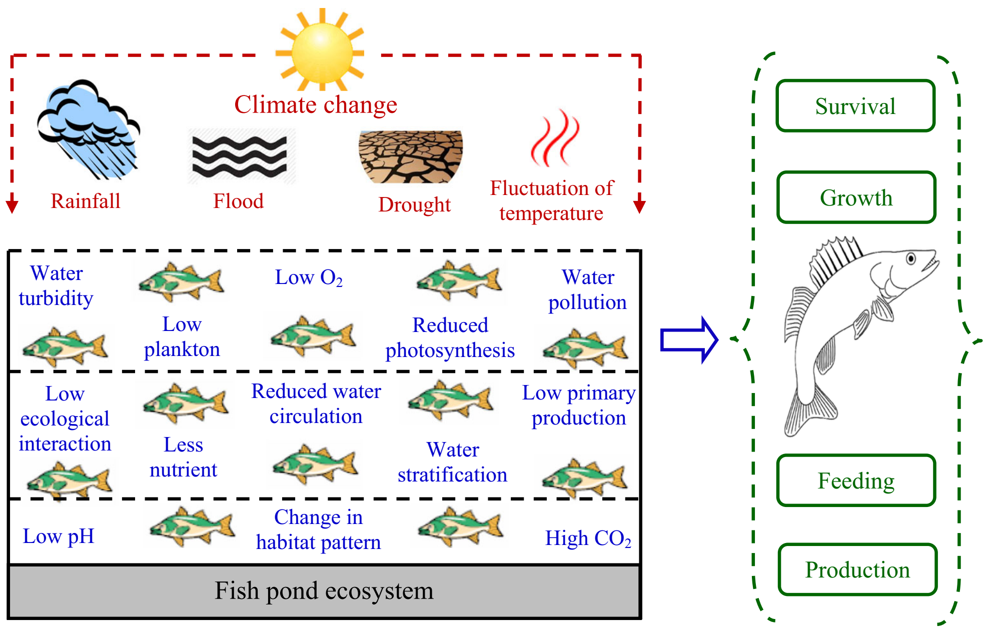

Fig. 3 Impacts of climate change on pond ecosystem with its potential effects on survival, growth, feeding and production of fish (based on field survey)

Table 2 Impacts of climatic variables on hatchery operation with fry supply, demand and price

Climatic variable	Fish reproduction and hatchery operation	Fry		
		Supply	Demand	Price
Flood	Flooding of broodstock ponds	Moderate	Decrease	Decrease
	Deteriorating water quality			
	Poor quality fry production			
Drought	Low water level in broodstock ponds	Moderate	Decrease	Decrease
	Stress in broods			
	Low quality fry production			
Rainfall variation	Shift in breeding season	Decrease	Moderate	Increase
	Affect succession of breeding			
	Low fecundity			
Temperature fluctuation	Stress in broods	Decrease	Moderate	Increase
	Low feeding by broods			
	Reduced spawning rate			

has had a great impact on fish reproduction. Late rainfall may cause a shift in breeding season and affect success of breeding, thus low fecundity. Although artificial rain often creates good breeding conditions in hatcheries, the spawning rate of fish remains lower than that of natural environment. Water quality parameters in fish hatcheries are also affected by rainy days with long periods of cloudy weather. Poor water quality and reduced light intensity affect spawning of fish (Steeby and Avery 2005).

According to hatchery operators, increased water temperature above 30 °C has led to stress in broodstock. Cessation of feeding by broodstock is one of the stresses by high water temperature. In order to keep body temperature normal, most broodstock lay at the bottom of the tank during high water temperature. Conversely, metabolism of broodstock becomes slow during low water temperature. Overall, changes in water temperature affect hatching rate and spawning of fish (Steeby and Avery 2005). Climate change has profound effects on the availability of wild prawn postlarvae in coastal Bangladesh, because of low spawning rate (Ahmed et al. 2013).

Grow-out operation

Changes in climatic variables severely affect fish grow-out operation. Mean ordinal rank indicated that poor water quality was the most significant impact on pond-fish culture, followed by fry mortality, high water temperature and low feeding. Conversely, the least important impact of climatic variables on aquaculture was decay of fish feed, followed by reduced culture period, inadequate water in ponds and increased production costs (Table 3). Kendall's *W* value was slightly higher for carp (0.59) than tilapia (0.53) and pangas (0.52) farming.

Field survey revealed that flood, drought and intense rainfall have adverse effects on fish stocking due to poor water quality that leads to fry mortality. High temperature of pond water during summer also causes death of fish fry. High water temperature can cause suffocation of fish, resulting in gulping at the surface layer of ponds due to low oxygen. Farmers reported that critically low oxygen concentrations occurred in the early morning, and thus fish face hypoxic conditions. Low oxygen concentrations can occur in the early morning following night that diminish oxygen production from photosynthesis, but respiratory demand by fish is similar (Tucker and Hargreaves 2004). According to key informants, high water temperature increases physiological activities of fish that increases the oxygen demand which in turn reduces dissolved oxygen in ponds. Farmers also reported that low feeding rate by fish is also caused by high water temperature. Warm water may also lead to fish mortality (Ficke et al. 2007).

According to our survey, climate change has increased grow-out operating costs by 15–20 % because of water management and increased input costs. A number of better-off farmers tend to spend money for irrigation ponds in the dry season. However, small-scale farmers cope with water scarcity in ponds by reducing fish culture period. Moreover, farmers often apply low amount of feed as the price of feed ingredients has recently increased. Climate change has an adverse impact on the supply of fishmeal from capture fisheries (Barange and Perry 2009). The decay of fish feed is also concerned for grow-out operation as wet conditions with temperature fluctuations influence the process of fermentation.

Prevalence of parasites and diseases

Field survey revealed that parasite infestation in fish ponds has increased due to changes in climatic variables because of increased transmission opportunity. Floodwater with pollutants and toxins allows parasites in fish ponds that may cause parasite epizootics. Farmers reported that the distribution of parasites increased in summer. The parasite life cycle is directly related to temperature as warmer water allows higher survival and growth of parasites, leading to fish infection (Marcogliese 2001).

According to farmers, changes in weather patterns have increased susceptibility to fish diseases, including black spot, white spot and epizootic ulcerative syndrome (EUS). The risk of pathogens for EUS has increased as a result of climate change (Marcos-López et al. 2010). Farmers reported that greater exposure to fish disease is one of the major threats during the winter season, because cold weather can spread pathogens in ponds. Moreover, disease outbreaks in pangas typically occur in the rainy season.

Table 3 Ranking of farmers' opinions for the effects of climatic variables on fish grow-out operation

Effect	Farming system									Mean ordinal rank[b]
	Carp (n = 50)[a]			Pangas (n = 50)[a]			Tilapia (n = 50)[a]			
	Score mean ± SD	*W* value	Chi-square (χ^2) value	Score mean ± SD	*W* value	Chi-square (χ^2) value	Score mean ± SD	*W* value	Chi-square (χ^2) value	
Poor water quality	4.94 ± 0.24			4.82 ± 0.44			4.86 ± 0.40			1
Fry mortality	4.78 ± 0.42			4.60 ± 0.53			4.64 ± 0.66			2
High water temperature	3.92 ± 0.27			3.78 ± 0.42			3.74 ± 0.63			3
Low feeding	3.86 ± 0.35	0.59	232.39	3.64 ± 0.48	0.52	204.33	3.78 ± 0.46	0.53	206.69	4
Increased production costs	3.72 ± 0.45		$P < 0.0001$	3.52 ± 0.50		$P < 0.0001$	3.70 ± 0.54		$P < 0.0001$	5
Inadequate water	3.66 ± 0.48			3.50 ± 0.51			3.68 ± 0.55			6
Reduced fish culture period	3.58 ± 0.54			3.44 ± 0.54			3.58 ± 0.61			7
Fish feed decay	3.56 ± 0.50			3.42 ± 0.49			3.40 ± 0.78			8

[a] n number of farmers

[b] Based on mean scores of all farming systems

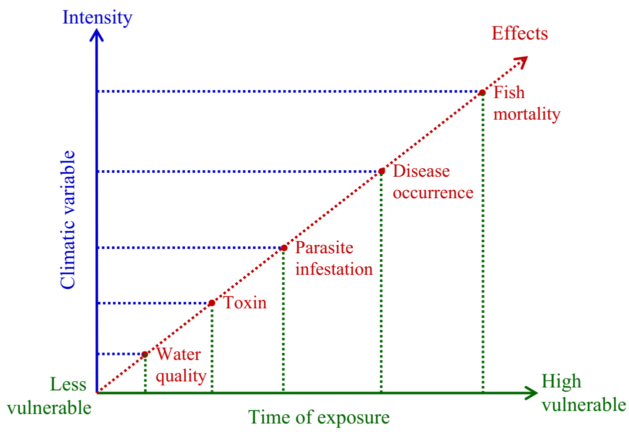

Fig. 4 Effects of climatic variables on parasite infestation and disease occurrence that cause fish mortality; *dotted lines* show sequential effects by climatic variable with intensity and time of exposure (based on field survey)

Field survey also revealed that high water temperature in fish ponds increases the intensity and frequency of disease outbreaks. A longer hot season raises water temperature leading to boost pathogenic bacteria in fish ponds (Karvonen et al. 2010). The possibilities of disease occurring among filter feeding fish could be higher as a result of changes in temperature (De Silva and Soto 2009). Increase in water temperature may also increase the possibility of shrimp disease (Alborali 2006).

Ultimately, prevalence of parasites and diseases can affect growth of fish that lead to increase mortality (Fig. 4). According to key informants, aquaculture productivity as well as profitability often fluctuates by disease outbreaks. Disease-affected aquaculture can threaten the viability of the fish marketing sector because of reducing the value of harvested fish.

Adaptation strategies

Holistic adaptation planning may help to reduce the impacts of climate change on pond-fish culture (Table 4). Field survey revealed that fencing and netting around ponds may prevent escape of stocked fish as well as invasion of predator fish during floods. The construction of higher pond-dikes is also one of the key strategies for flood management. Moreover, community-based flood control devices (dams, embankments) may help to protect inundation. Community-based climate change adaptation strategies have been suggested for prawn farming in southwest Bangladesh (Ahmed et al. 2014a). According to key informants, community-based water embankment could turn open-water bodies to productive use through floodplain aquaculture. Short-cycle fast growing fish species (barb, tilapia and silver carp) can be cultured in

Table 4 Adaptation strategies to climate change for freshwater aquaculture

Climatic variable	Adaptation strategy
Flood	Netting and fencing around ponds
	Construction of higher pond-dikes
	Community-based flood protection
	Opportunities for floodplain aquaculture
Drought	Community-based irrigation facilities
	Pump-out groundwater
	Micro-irrigation for pond-dike cropping
	Adjusting fish culture during monsoon
Rainfall variation	Rainwater harvesting
	Using rainwater for fish culture
	Applying rainwater for pond-dike cropping
	Multiple stocking and harvesting of fish to reduce risk
Temperature fluctuation	Plantation of fruit trees on pond-dikes
	Vegetation on pond-slopes
	Growing aquatic weeds in ponds for shelter of fish
	Pond water exchange for reducing temperature

seasonally flooded water bodies. Open-water cage culture has already been introduced to adapt climate change (Shelton 2014).

Community-based irrigation facilities may provide aquaculture opportunity in the dry season. Key informants suggested that pumping groundwater to irrigate ponds can be fed through aquaculture. Pond water can also be used for irrigating dike crops. Micro-irrigation[7] for pond-dike cropping can increase water efficiency (Dukes et al. 2010). Pond-fish culture with dike cropping is considered as integrated aquaculture-agriculture that produces "more crop per drop" (Ahmed et al. 2014b). Adjusting fish culture during monsoon may also help to cope with drought.

Rainwater harvesting with storage facilities may help for aquaculture in the dry season. Using rainwater for fish culture and pond-dike cropping may increase water use efficiency. Rainwater harvesting is a primitive idea for improving water efficiency. Rainwater harvesting and supplementary irrigation in cropland has a key role in increasing food production (Wisser et al. 2010). According to key informants, multiple stocking and harvesting of fish may help to reduce the risk of crop failure during monsoon.

Pond-dike cropping can help to cope with increased water temperature. Plantation of fruit trees (banana, coconut, guava, lemon and papaya) on pond-dikes can provide shade on water for fish. Pond-slopes can also be used for growing vegetables (bean, cucumber and gourd) that can be

[7] The World Food Prize 2012 was awarded to Dr Daniel Hillel for his role in implementing micro-irrigation.

extended out onto the pond water with bamboo structures. Moreover, a small part of aquatic weeds including azolla, duckweed, water hyacinth and water spinach can be grown in ponds to provide shelter for fish during high water temperature. Pond water exchange may also help to reduce heat during summer. Water exchange and mixing can help in maintaining water quality, reducing fish mortality and disease control (Tucker and Hargreaves 2004).

Conclusions

The evidence of this study confirmed that climate change has adverse impacts on freshwater aquaculture. Pond-fish culture has been threatened by different climatic variables, including flood, drought, rainfall variation and temperature fluctuation. These climatic variables have had dramatic effects on the ecosystem of ponds and thus survival, growth and production of fish. Changes in climatic variables have adverse effects on fish reproduction, grow-out operation, parasite infestation and disease occurrence. Future climate change would have serious consequences for pond-fish culture.

With regard to climate change, there is a challenge to the sustainability of pond-fish culture. In order to sustain fish culture with climate change, integrated adaptation strategies have been proposed. Community-based adaptation strategies for flood control and irrigation facilities have been suggested to reduce the effects of climate change on fish culture. Efficient use of rainwater may also help for fish culture and pond-dike cropping. Moreover, plantation on pond-dikes and water exchange can help to keep water cool during summer.

In order to implement proposed adaptation strategies, capacity building of fish farming communities is needed. Institutional support may also help to implement adaptation strategies. Further research is also needed to understand better adaptation strategies for sustainable freshwater aquaculture in rural Bangladesh to meet environmental challenges.

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