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Title: Evaluating the contribution of diversified shrimp-rice agroecosystems in Bangladesh and West Bengal, India to social-ecological resilience

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Abstract

Shrimp-rice farming practices in the coastal areas of Bangladesh and West Bengal, India are reviewed. It is apparent that this integrated aquaculture-agriculture system is suited to environmental and hydrological conditions found in specific areas. Production strategies devised by farmers demonstrate that the diversified culture of shrimp with rice is technically feasible. Shrimp-rice agroecosystems exhibit several synergistic effects between systems components that result in efficient resource use and enhanced production, whilst avoiding negative environmental impacts. Integrated cropping enhances agrobiodiversity and reduces dependence on external inputs (agrochemicals, feed and fertiliser). Diversified shrimp-rice culture produces a valuable export crop, stimulating economic development and staple cereal, fish and vegetable crops that enhance human nutrition and food security. The contribution that diversified shrimp-rice agroecosystems make to social-ecological resilience is evaluated using the DPSIR (Driving forces, Pressures, State, Impacts, Responses) framework. Strengths, Weaknesses, Opportunities and Threats (SWOT) associated with prevailing practices are reviewed using the SWOT framework. We conclude, that with appropriate safeguards, diversified shrimp-rice agroecosystems could contribute to climate change adaptation and enhance production from land affected by salinization. Policy-support and practical action is needed to support and promote diversified shrimp-farming agroecosystems as they can contribute to social-ecological resilience in vulnerable coastal communities.

Keywords: diversified shrimp-rice agroecosystems; social-ecological resilience; human nutrition; food security; climate change adaptation

1. Introduction

Intensification within terrestrial and aquatic farming systems and the transition to monoculture-based production have resulted in an imbalance between the appropriation of ecosystem services and regenerative capacity of ecosystem support areas, eradication of agrobiodiversity and loss of resilience to: pests and diseases, adverse environmental shocks and trends, input and commodity price fluctuations (Davies et al., 2009; Vie et al., 2009; Hoffman et al., 2010). An urgent need to address these issues was highlighted by the signatories to the United Nations' post-2015 agenda for sustainable development 'Transforming our world: 2030 Agenda for Sustainable Development' (UN, 2015). In support of Goal 2 focused on food security, human nutrition and sustainable agriculture, Target 2.4 specifies the need to ensure sustainable food production and yield increases. Immediate action needed to reverse biodiversity loss was specified in the 'Strategic Plan for Biodiversity' adopted by the parties to the United Nations' Convention on Biological Diversity (CBD, 2016). One of the Aichi Targets that constitute the plan (Target 7) specifies that 'By 2020 areas under agriculture, aquaculture and forestry are managed sustainably, ensuring conservation of biodiversity'. Considering food security, a perfect-storm of global population growth, increased resource competition and worsening climate change impacts threaten conventional food production systems (Beddington, 2010; Godfray et al., 2010). With climate change expected to increase risks due to more frequent 'intense precipitation events' and more 'extreme rainfall and winds associated with tropical cyclones' in South Asia (Conway and Wagge, 2010) it is imperative that food producing systems in the region are made resilient and adaptable to changing climate conditions.

Intensive monoculture of brackish water shrimp (*Penaeus monodon*), using high stocking densities and formulated feeds, developed rapidly throughout Asia in the 1980s and often outpaced environmental protection measures and legislation causing major environmental and social problems (Naylor et al., 1998). Significant areas of mangrove forest and agricultural land were converted to shrimp farms (Valiela et al., 2001; Hamilton, 2013). Countless millions of wild shrimp post-larvae were caught annually to stock the farms, and in the process vast numbers of by-catch of other species were discarded (Hoq, 2000). Rapid and unregulated development of farms in promising locations routinely exceeded the carrying capacity of the receiving environment, resulting in environmental degradation and self-pollution (Beveridge and Phillips, 1993; Phillips et al., 1993; Islam et al., 2006). Restrictions imposed on access by local communities to coastal resources, physical displacement of rice farmers and coastal communities and sometimes violent disputes caused social and law and order problems (Deb, 1998; EJF, 2004).

With large areas of coastal land in the Philippines formed into brackish water fishponds the economic, institutional and legal barriers to converting them back to mangrove were considered severe (Samson and Rollon, 2008). Restoration efforts often resemble forest plantations and fail to replicate the biological diversity and ecological functioning of undisturbed mangroves (Ellison, 2000). Shrimp ponds abandoned following problems with intensive culture were not generally replanted with mangrove but instead producers reverted to traditional production modes. Such practices do not require cultured shrimp seed inputs (possibly harbouring disease) or external fertiliser and feed inputs and do not incur significant costs. Thus, reducing shrimp and environmental health and financial risks, but producing less shrimp biomass per unit area.

Assessment of culture strategies in the Mahakam Delta, East Kalimantan, Indonesia showed that traditional production, based on natural stocking with animals entrained in incoming tides continues. Harvests of wild shrimp (49 kg ha^{-1} y^{-1}) supplemented by wild crab catches (10.3 kg ha^{-1} y^{-1}) generated a 113% return on operating costs (Bunting et al., 2013). As compared with only 27% for semi-intensive production, when investment costs and risks associated with production are substantially higher. Whilst extensive and traditional systems are often considered ecologically-sound several potentially unsustainable practices are apparent. Shrimp aquaculture development has been responsible for the clearance of large mangrove areas, and production rates per unit area in extensive systems are low as compared with semi-intensive systems, thus appropriating larger physical areas to produce the same yield (Bunting, 2001). Sustainable intensification within selected areas to enhance production levels could spare other areas for coastal habitat restoration.

Potential means to sustainably intensify aquaculture production from coastal areas include low-impact approaches to shrimp farming: integrating shrimp culture with mangrove plantations (Johnston et al., 1999; Fitzgerald, 2002); cultivating haylophytes or seaweed downstream of shrimp culture (Briggs and Funge-Smith, 1996; Bunting and Shpigel, 2009); integrating fish, prawn and shrimp culture with rice and vegetable cultivation, together, or in a rotation (Azad et al., 2009; Faruque et al., 2017). Approaches to culturing fish and prawns within rice fields and associated benefits are broadly understood (Little et al., 1996; Amilhat et al., 2009; Ahmed and Garnett, 2010). The potential and practicalities of integrating shrimp and rice culture are less well documented. Consequently, the aim of this review is to assess the contribution that integrated shrimp-rice farming could make to social-ecological resilience sustaining livelihoods and communities adjacent to the Sundarbans of Bangladesh and West Bengal, India. Finally, opportunities to promote shrimp-rice culture in appropriate areas for enhanced resilience and to help rehabilitate salinized and degraded tropical coastal zones are considered. We do not, however, advocate transferring shrimp culture inland, beyond brackish water areas. This can promote the salinization of land and water resources and significantly increase pressure on freshwater resources (Tran et al., 1999; Flaherty et al., 1999, 2000; Belton and Little, 2008).

2. Materials and Methods

2.1. Study site

The Sundarbans is the largest expanse of mangrove forest globally covering 10,000 km^2, located across the northern shore of the Bay of Bengal between Bangladesh and India (Figure 1). The Sundarbans Reserve Forest in Bangladesh covers 6000 km^2 of which 30% is water bodies (UNESCO, 2016). UNESCO (United Nations Educational, Scientific and Cultural Organization) inscribed the Sundarbans of India and Bangladesh in the list of World Heritage Sites in 1987 and 1997, respectively.

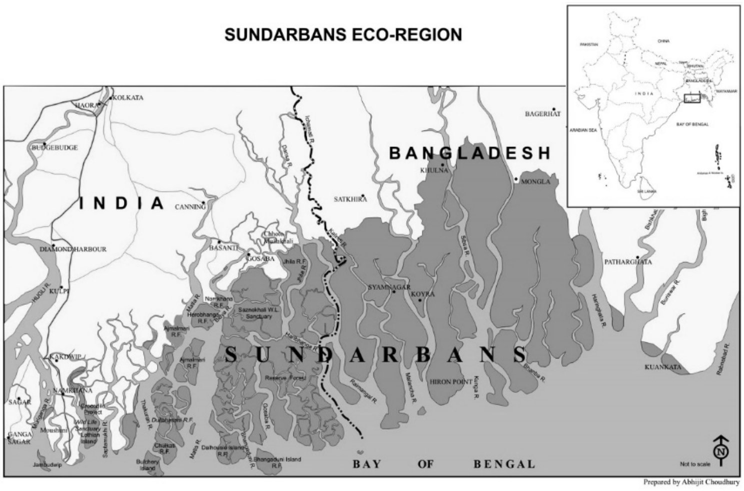


Figure 1. Trans-boundary Sundarbans mangrove forest of Bangladesh and West Bengal, India (source WWF-India, 2017; © 2017 WWF. Some rights reserved)

2.2. Review frameworks

Commencing with a description of current culture practices and technologies used, the role of shrimp-rice culture in food security is assessed. The contribution of shrimp-rice agroecosystems to social-ecological resilience within coastal livelihoods and communities is reviewed. Prospects for adaptive polices and management responses to sustain systems, given current anthropogenic pressures and worsening climate change impacts, are discussed and options to promote wider resilience assessed. The role that shrimp-rice agroecosystems have played in promoting social-ecological resilience are reviewed using the DPSIR (Driving forces, Pressures, State, Impacts, Responses) framework. This conceptual framework has been demonstrated to be effective at structuring an assessment of environmental and socio-economic issues in support of policy development (Maxim et al., 2009). Responses that could enhance exiting practices and promote adoption in promising new areas are also identified. The SWOT (Strengths, Weaknesses, Opportunities and Threats) framework is used to assess prospects for shrimp-rice culture to enhance social-ecological resilience given existing and potential future environmental, social and economic conditions.

3. Results and Discussion

3.1. Traditional shrimp-rice culture systems

Combined culture of shrimp with rice presents challenges that have been overcome through immanent development and innovation. Integration of giant freshwater prawn (*Macrobrachium rosenbergii*) with rice farming in Bangladesh has been described extensively and the benefits of gher systems (fishponds with shallow central areas for rice cultivation) are well known and evaluated (Belton and Azad, 2012; Ahmed and Garnett, 2010; Ahmed et al., 2008, 2010a, 2014). Systems for the integration of marine shrimp and rice culture have been described to a lesser extent, for example, Wahab et al. (2003) and Azad et al. (2009). These accounts point to several important techniques and innovations that make such systems interesting to evaluate from the perspective of social-ecological resilience (encompassing food security and climate change adaptation). Resilience in this context was described by Adger et al. (2005) as the ability of a socio-ecological system to recover from natural disasters and retain essential linkages between ecosystems and society. Synergies between shrimp culture, rice cultivation and environmental sub-systems of shrimp-rice agroecosystems are summarised in Figure 2.

Considering the resilience of activities, it is important to place developments within an historical context. Thus, giving insight to the continuity of activities, evolution of practices in response to environmental and socioeconomic shocks and trends and intergenerational arrangements and transfers. Traditional shrimp farming reportedly commenced in the 1820s in the mangrove areas of Bangladesh (Azad et al., 2009). Extensive engineering works in Bangladesh and West Bengal in the 1960s to transform marginal lands for cereal crop cultivation as part of the Green Revolution initiatives made large coastal areas accessible for settlement by a substantial migrant workforce. After a few years under rice cultivation a sizable proportion of this land was transformed into ponds for aquaculture. Mangrove cutting on the seaward side of the newly formed embankments opened up these areas for rapid and extensive shrimp pond construction. Conversion of mangroves to aquaculture in Bangladesh and India in the main culture areas between 1972 and 1989 accounted for 7% and 4%, respectively, of the historic forest area (Hamilton, 2013). Significantly less than in several other countries and this can be attributed to government action to protect the trans-boundary Sundarbans mangrove forest.

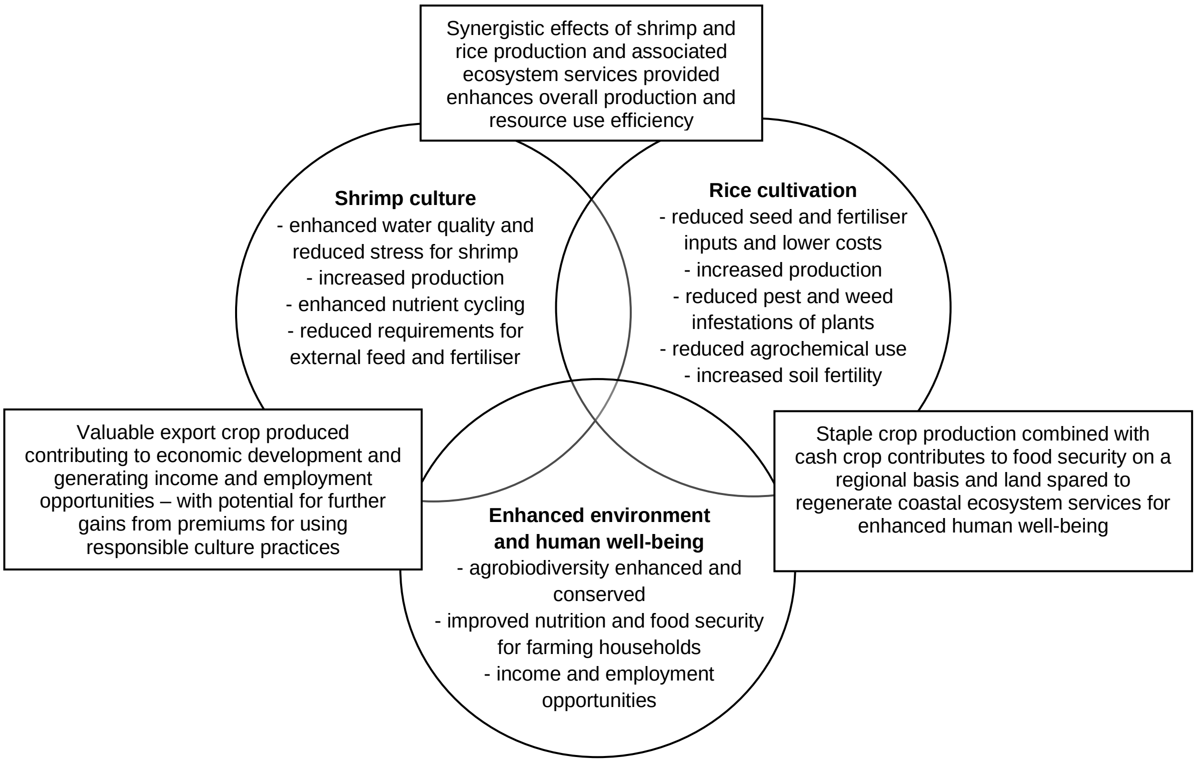


Figure 2. Intersection of economic and social development and environmental protection for diversified shrimp-rice agroecosystems

Historically, the Sundarbans mangrove forest provided an important habitat for shrimp. Channels and low-lying depressions in the Sundarbans, earlier used by poor fishers, have been turned into shrimp farms (Islam and Wahab, 2005). Declining production in countries where shrimp farming was first established, owing to water and sediment quality problems and shrimp disease outbreaks, contributed to higher shrimp prices globally and prompted commercial, export oriented shrimp culture development during the 1980s in Bangladesh and India (Azad et al., 2009;

Vivekananda et al., 2014). Moreover, Milstein et al. (2005) noted that shrimp aquaculture in Bangladesh contributed to economic development in coastal areas.

Developments in the neighbouring Sundarbans in West Bengal, India followed a similar trajectory with large mangrove areas cleared as settlements were established for migrant workers brought from Midnapore District, West Bengal and neighbouring Odisha (formerly Orissa) (Naskar, 1985). Prior to the construction of embankments and irrigation canals by the Department of Irrigation in 1967 farmers in Minakhan Block depended solely on an autumn crop of 'kharif' rice leading to an absence of food security. Others with access to land on the seaward side of the main embankments built a series of secondary dikes enclosing large areas to allow them to practice brackish water aquaculture. Observing the success of these producers with fish and shrimp culture, others constructed canals to carry brackish water to their rice fields to permit the combined production of fish and shrimp with rice.

Coastal areas in southwest and south-central Bangladesh influenced by the Ganges-Brahmaputra-Meghan Rivers, and southeast influenced by the Matamuhuri River, have been brought under aquaculture production through the construction of 'bheris' or large impoundments (Azad et al., 2009). With areas ranging from 1 ha up to 100 ha and located in low-lying coastal areas they are filled with incoming tide. This water carries a diverse array of juvenile marine animals into the ponds where they are retained by closing gates in the seaward embankments. Traditional management practices consist of regulating water exchange, with no supplementary stocking of juveniles, feeding or fertilisation. The ghers developed in an uncoordinated manner in the southwest, with shared dikes restricting options for water management (Azad et al., 2009). Farmers generally culture shrimp (*P. monodon*), although if brackish water is available they may integrate prawn (*M. rosenbergii*) and winter rice culture (Jan-July), followed by prawn monoculture from July to December. In the central-coastal areas, farmers cultivate crops such as rice, vegetables or water melon or have a fallow period in the dry winter season (Jan-May), followed by integrated prawn-rice farming in the wet summer season (June-Dec).

Table 1. Typical values for production system elements indicated for shrimp and diversified shrimp-rice agroecosystems

Production system element	Agroecosystem	
	shrimp§	shrimp-rice§§
Physical characteristics		
Salinity range (ppt)†	7 to 15	2 to 8
Average pond area (ha^{-1})††	0.2 to 1.5	0.5 to 5.0
Average gher area per household (ha^{-1})†	0.9	0.4
Inputs		
Shrimp post-larvae (number ha^{-1} y^{-1})††	8,000 to 25,000	8,000 to 15,000
Post-larvae survival (%)††	<50%	<35%
Lime (kg ha^{-1} y^{-1})††	100	150
Cow dung (kg ha^{-1} y^{-1})††	500	420‡
Labour (days ha^{-1} y^{-1})††	50 to 150	100 to 180
Production		
Cultured shrimp harvest size (g)††	30 to 50	30 to 50
Cultured shrimp biomass (kg ha^{-1} y^{-1})†	295	171
Wild shrimp (*Metapenaeus monoceros*) (kg ha^{-1} y^{-1})††	22.1	24.1
Fin fish (kg ha^{-1} y^{-1})†	128	269
Rice (kg ha^{-1} y^{-1})†,††	-	1149 to 3133
Vegetables (kg ha^{-1} y^{-1})†	-	1837
Household consumption		
Rice (kg) and [% of production] †	-	878.4 [57]
Vegetables (kg) and [% of production] †	-	74.5 [11]
Fish (kg) and [% of production] †	30.9 [42]	42.8 [34]
Shrimp/prawns (kg) and [% of production] †	4.4 [2]	10.2 [5]
Total (kg) and [% of production] †	38.5 [13]	1145.7 [45]
Cost-Benefit Analysis		
Aquaculture costs (US$ ha^{-1})†	1007	1408
Rice costs (US$ ha^{-1})†	-	259
Vegetable costs (US$ ha^{-1})†	-	75
Returns (US$ ha^{-1})†	1918	4119
Net profit (US$ ha^{-1})†	911	2377

Data source: †Faruque et al. (2017); ††Chowdhury et al. (2010).

Notes: §shrimp culture routinely yields a by-crop of brackish water and marine fin fish; §§shrimp-rice culture occurs in intermediate salinity areas where it is possible to produce crops of freshwater fish and vegetables; ‡'little or no' fertiliser or cow dung use was noted (Chowdhury et al., 2010, p84) but assuming the cost of cow dung was the same as for shrimp producers an amount was calculated based on the expenditure data presented (p89).

Farming practices in the southeast consist of shrimp culture, rotating with salt production and rice farming, and in highly saline areas farmers are confined to shrimp farming. Production characteristics for shrimp culture in high salinity areas and shrimp-rice culture in intermediate salinity area are summarised in Table 1.

The total area under prawn and shrimp cultivation in Bangladesh was estimated at 275,583 ha in 2015 of which 216,468 ha was under shrimp farming and the remainder under prawn farming (DoF, 2016). Based on 2004 data the area covered by shrimp farming in Bangladesh was estimated at 148,000 ha on more than 16,000 farms (Azad et al., 2009). A survey by these authors revealed that virtually all (97.5%) producers in the central region cultivated both rice and prawns. In shrimp producing areas it was observed that when brackish water was available, *P. monodon* and winter rice were farmed simultaneously between January and July.

3.2. Technological developments

Despite a long history of shrimp farming in Bangladesh, which it might be assumed would have developed into input intensive and technologically demanding practices, Islam et al. (2005) noted that over 90% of shrimp farmers employ extensive-traditional production strategies. Practices that appear to make such production systems financially viable include: an absence of mechanical pumps and aerators, instead depending on tidal exchange of water; reliance on natural recruitment of animals entrained with incoming tides; avoidance of costs for inorganic fertiliser and synthetic pesticides and modest requirements for animal manure to enhance production. Continued dependence on wild post-larvae entering ponds is regarded as detrimental, however, and would prohibit organic certification under Naturland (2005) standards.

Shrimp post-larvae certified specific pathogen free (SPF) are available in West Bengal and are supplied by road and rail from hatcheries in Andhra Pradesh and Odisha (Mr Bhadauria, shrimp hatchery operator, personal communication). Initial developments in shrimp seed production occurred in central government facilities. The private sector, supported by consultancy inputs from the USA, then rapidly emerged as a more efficient and effective producer. Shrimp are stocked at a rate of 7000 ha^{-1} every 15 days and can be harvested after two months; shrimp account for 65-70% of the revenue generated. Production in the intermediate salinity zone (6-7 ppt) was reported to involve fish (Indian major carp, mullet, Asian seabass) culture for six months until July. Alternatively, high densities of tilapia are stocked with more valuable Asian seabass, that feed on the smaller tilapia. Rice is planted on 85-90% of the area when the rains come and the salinity falls to 3-4 ppt; a proportion of the area is left unplanted to enable simultaneous fish culture. The extent of diversified shrimp-rice agroecosystems in West Bengal appears to be significantly less than that in Bangladesh.

An account of shrimp farming trials following the harvest of rice from ghers in Khulna District, southwest Bangladesh is given by Islam et al. (2005) who monitored a selection of small (1-5 ha), medium (6-10 ha) and large (>10 ha) ponds managed in a comparable manner. Ponds were ploughed after the rice harvest and left to sun-dry for a week in early January, then treated with 200-250 kg ha^{-1} lime (dolomite), then 7 to 10 days later 50 kg ha^{-1} of both urea and triple-super phosphate fertiliser. Coinciding with the high-tide in February, ponds were then flooded with water 3 to 5 days after fertiliser application, inlets were screened to exclude wild juveniles, larvae and fertilised eggs. Post-larvae were stocked at a rate of 1.8-2.2 m^{-2} with a combination of hatchery reared and wild shrimp (*P. monodon*). Large ghers received no further inputs. Inorganic fertiliser and rice bran were applied intermittently to small and medium ghers. Partial water exchanges were made in all ponds when tides permitted. Market size shrimp were harvested from month three onwards, partial harvests and re-stocking proceeded for the remainder of the culture period. Shrimp remaining in the ghers were harvested during rice planting in late August to early September. Survival rates for stocked shrimp were lower in larger ghers (18%) as compared with 37% and 50% in medium and small ones, respectively (Islam et al., 2005). Consequently, yields were lowest in large ghers (80 kg ha^{-1} y^{-1}) as compared to 200 kg ha^{-1} y^{-1} in small ghers.

New technologies have not been adopted in shrimp-rice farming systems in Bangladesh as producers are probably averse to financial and shrimp health risks, given past failures and uncertainty over future input costs and shrimp prices (Muir, 2003). Connected through middlemen to international export markets, shrimp producers find themselves at the vagaries of global economic conditions and vulnerable to production increases elsewhere in the world. Perversely, climatic shocks, natural disasters, environmental hazards and disease outbreaks affecting other producing areas can benefit unaffected shrimp farmers, but given the international nature of the shrimp trade and general response of farmers elsewhere to invest in production at such times, these are usually short-lived.

Financial and shrimp health risks are minimised in extensive production, whilst total operating costs are reduced, helping producers avoid or at least lessen indebtedness. Shrimp farm establishment in southwest Bangladesh, according to Salam et al. (2003) was not systematic but driven by access to water and the influence of adjacent farmers. Evaluating financial returns from farms producing carp, crab, prawn, shrimp, tilapia and rice these authors noted that prawn culture generated the highest returns (US$ 2051 ha^{-1} y^{-1}), followed by brackish water shrimp and crab farming at US$ 1518 and 1385 ha^{-1} y^{-1}, respectively; rice culture generated the lowest returns (US$ 140 ha^{-1} y^{-1}).

3.3. Food security

The amounts and proportion of crops (aquatic and terrestrial) consumed by households operating shrimp-rice and shrimp culture systems are shown in Table 1. Households engaged in integrated shrimp-rice culture consume a greater amount and diversity of food they produce, thus making a more significant contribution to their food security. Consumption of even modest amounts of vegetables, fish and wild shrimp by adolescent girls, pregnant women and young children in farming households and local communities could have a disproportionate benefit on their health (1,000 Days, 2017). The diversity of crops produced and aquatic animals harvested from both systems highlights the need for a more nuanced approach in assessing and discussing such systems to avoid underplaying their significance for food security and livelihoods. We advocate adoption of the term 'diversified shrimp-rice agroecosystem' to reflect the true nature of the enterprise.

Cultured shrimp constitute a valuable commodity that is costly to produce and traded internationally, generating substantial export earnings for several developing nations. Consequently, very little cultured shrimp production in Bangladesh, for example, is destined for consumption by farming families or local communities. Instead farmers will sell shrimp and buy food with the resulting income; labourers will use their earnings to purchase staple food supplies (Toufique and Belton, 2014). Labourers and poor groups may previously have collected and fished for aquatic animals and gathered plants for consumption and medicinal purposes (Hoq, 2008). With the advent of land conversion for agriculture and aquaculture, opportunities for this have been restricted. Embankment construction and wetland conversion for shrimp farming has impeded wild fish migration, disrupted hydrological regimes and destroyed spawning and nursery areas, thus severely restricting the availability of small indigenous fish and other aquatic species, otherwise important in the diets, income and livelihoods of poor coastal and rural communities (Roos et al., 2007).

Filter-feeding carp (*Hypophthalmichthys molitrix* and *Catla catla*) were stocked in *ghers* on the majority (90%) of farms sampled in south-central Bangladesh and grass carp (*Ctenopharyngodon idella*) on 37.5% of farms in the southwest (Azad et al., 2009). Carp stocking was reported to enhance nutrient cycling leading to increased shrimp production, whilst farming families can consume these less valuable fish themselves. The volume and frequency of this consumption, and the extent to which farming families, labourers and other community members benefit was not explored in depth. Poor groups may be able to purchase low value by-catch from shrimp ponds and poor-quality shrimp, perhaps harvested early because of a disease outbreak, but this may expose them to greater public health risks. Prawn heads and legs are consumed by local communities at harvest time (Ahmed et al., 2010a) and this may be the same for shrimp. Shrimp heads and shells can be processed to shrimp paste for human consumption. Shrimp processing 'waste' can be used to produce meal and oil for incorporation in livestock and fish feed. Diversion of shrimp shell material to emerging biorefinery industries (Yan and Chen, 2015) may have implications for feed and food security.

Vegetables were grown on embankments or dikes constructed to enclose and separate ponds on 85% of farms surveyed in central Bangladesh and on 22.5% of farms in the southwest (Azad et al., 2009). Female family members cultivated vegetables on gher dikes in the central region and typical crops included beans and cowpeas (*Phaseolus vulgaris* and *Vigna unguiculata*), bitter gourd (*Momordica charantia*), okra (*Abelmoschus esculentus*) and pumpkins (*Cucurbita moschata*). When farmers cultivate rice, or grow other agricultural crops on dikes they may consume some of this. Labourers may be allowed to cultivate certain areas, to grow food for cooking whilst at work or to supplement household food supplies. Further research is needed to establish the significance of these activities to household livelihoods and resilience and potential risks of reconfiguring ponds or disruption to access arrangements. Enhanced agrobiodiversity resulting from the adoption of mixed farming systems can contribute to more resilient and productive farming systems (Bunting et al., 2015).

Regionally, combining the culture of valuable aquaculture species with rice would help maintain local levels of staple food production underpinning food security. Rice yields comparable to those from prawn-fish-rice culture of 2350 kg ha^{-1} y^{-1} (Ahmed et al., 2014) might be anticipated. Trials with the System of Rice Intensification (SRI) have demonstrated that modified management practices including lower planting densities, as used in shrimp-rice culture, can enhance rice production as compared with conventional paddy cultivation (Uphoff, 2012). Protection of land used to cultivate staple crops from conversion to other purposes is a priority in many countries and with heightened tensions globally around food security calls for tighter controls are set to intensify. When the production of staple crops can be integrated with aquaculture this may help allay such fears. Development of shrimp-rice farming in inland areas is not advocated here as the transfer of salt water inland can contaminate land and water resources and shrimp culture in such situations consumes huge volumes of freshwater (Tran et al., 1999; Flaherty et al., 1999, 2000; Belton and Little, 2008).

3.4. Social-ecological resilience

There are over two million people involved in prawn and shrimp production, marketing, processing and export in Bangladesh (WorldFish, 2013). The livelihoods of around 400,000 people, many of them women and children depend on wild fry fishing in coastal Bangladesh (Ahmed et al., 2010b). Catching shrimp post-larvae is unsustainable and extremely damaging to marine biodiversity and causes health problems for those involved. Collecting post-larvae was banned or restricted in selected areas in 2000 and development agencies, government departments and NGOs are attempting to promote livelihoods diversification for those engaged in this activity (Ahmed et al., 2010b). Many people continue to catch post-larvae, however, as: they have the equipment, knowledge and experience to make money; it fits with their other livelihood activities and responsibilities; people may not have the required assets or opportunities to pursue alternative livelihoods; there continues to be a market for wild shrimp seed.

Employment associated with shrimp aquaculture has been created in both on- and off-farm activities in coastal areas, including jobs supplying inputs and processing production for export (Hamid and Alauddin, 1998). Labour requirements for shrimp farming using increased technological inputs have been cited as a potential advantage of greater intensification, as opposed to more intensive agricultural management that tends to reduce labour requirements (Hamid and Alauddin, 1998) although it was noted that not all shrimp farming areas are suited to more intensive production. Emerging industries based on converting seafood processing waste into value added products (Yan and Chen, 2015) could create significant new income and employment opportunities. Concerning on-farm work and employment in processing plants it has been speculated that operators bring in workers from outside the community owing to mistrust and concerns over losing control to local groups (Hamid and Alauddin, 1998). Consequently, employment benefits of commercial shrimp farming to coastal communities may have been overstated.

According to Milstein et al. (2005) when commercial shrimp farming first developed, ghers were large (100-400 ha) had low yields and were owned by the rich. This was not considered an acceptable situation by many and proposals were made to reduce the size of ghers to promote equality and better management. Provisions in the Land Reform Board Act, 1989 were included to achieve this but problems were reported with implementation. Research in southwest Bangladesh between 2011 and 2012 found that gher farming in intermediate salinity zones was characterised by 'strong social networks' and 'good access to information and within and between villages' (Faruque et al., 2017). Institutional innovation in the form of 'gher leasing markets' was cited as a 'source of resilience and adaptive capacity' as poorer farmers can lease out their land and receive an income without incurring financial costs.

In neighbouring West Bengal, feudal landholdings were redistributed through land reforms. In the case of water-bodies, however, it was difficult for households to manage their allotted portion and consequently many were converted to rice farming; with plots more easily managed by individuals but realising lower financial returns per unit area. In concert with land reforms the Government of West Bengal actively promoted self-help group (SHG) formation as a prelude to formal establishment of registered co-operatives. Land reforms and subsequent pond-use dynamics in the East Kolkata Wetlands adjoining the Sundarbans in West Bengal are described in detail elsewhere (Bunting et al., 2010). The influence of the emerging aquaculture sector in Bangladesh, and shrimp farming in particular, on gender roles, responsibilities and relationships has been broadly assessed (Deb, 1998; Hamid and Alauddin, 1998; DTS, 2006).

The Sundarbans of Bangladesh and West Bengal has a population of over 4 million and the livelihoods of around 1.2 million people depend on extraction of natural resources including bees-wax, birds, crustaceans, fish, fruit, honey, medicinal plants, molluscs, turtles and wood (Chowdhury, 2010). Over 400 species of fish have been identified in the Sundarbans (Islam and Wahab, 2005) and in Bangladesh they are harvested by between 110,000 and 291,000 fishers using 25,000 registered fishing boats. Value chains for products derived from the Sundarbans mangrove also generate employment locally in terms of farming and labouring and in processing and marketing that usually takes place further inland, but may still constitute employment for poor and vulnerable groups.

The remaining Sundarbans area is of great socioeconomic importance for coastal communities, notably poor and marginal groups that can construct subsistence-based livelihoods, dependent on access to provisioning ecosystem services sustained by this trans-boundary mangrove. These livelihoods are not necessarily sustainable or particularly resilient. Low incomes and poor socio-economic conditions, difficulties in accessing education, health services and safe drinking water supplies are compounded by poor transport and communication links that limit opportunities for livelihoods diversification (ADB, 2008; Danda et al., 2011). Many inhabitants on the periphery of the protected forest area exist below the official poverty line and still depended entirely on firewood for cooking, thus increasing pressure on the Sundarbans. The delta also receives huge volumes of untreated wastewater discharged to rivers upstream and natural processes act to purify this and protect adjacent coastal areas. The mangrove area provides a buffer against cyclones and storms, thus protecting millions of people in coastal and low-lying areas inland. Mangrove restoration in high salinity areas formerly occupied by shrimp ponds could contribute to enhanced social-economic resilience through increased stocks and flows of ecosystem services. Adopting good practices that have been proven elsewhere could increase the chances of successful mangrove regeneration (Fitzgerald, 2002).

3.5. Adaptive planning and management responses

Coastal communities living on the fringes of the Bay of Bengal, from Odisha and West Bengal, India, through Bangladesh, to Myanmar are frequently subjected to storms, cyclones and floods. Since 2007, the region has been affected by tropical cyclones Sidr, Nargis, Bijli, Aila and Mahasen. Anthropogenic pressures notably mangrove clearance and reclamation of low-lying areas for agriculture, aquaculture and settlements have increased the level of exposure and frequency of potentially devastating events. Climate change impacts including sea level rise and extreme weather events threaten to exert greater pressure on Sundarbans communities and ecosystems, compounding development challenges (Conway and Waage, 2010). Sinking of many deltas around the world has been reported owing to accelerated compaction, induced by anthropogenic activities such as water, gas and oil extraction (Syvitski et al., 2009). This will exacerbate these problems, increasing vulnerability of coast communities, including those in the Ganges-Brahmaputra-Meghan system flowing through the Sundarbans. Mangrove colonisation of newly accreted sediments in the delta is reportedly occurring (FAO, 2007), but development of this potential new buffer is not uniform and will not compensate for mangrove loss already witnessed.

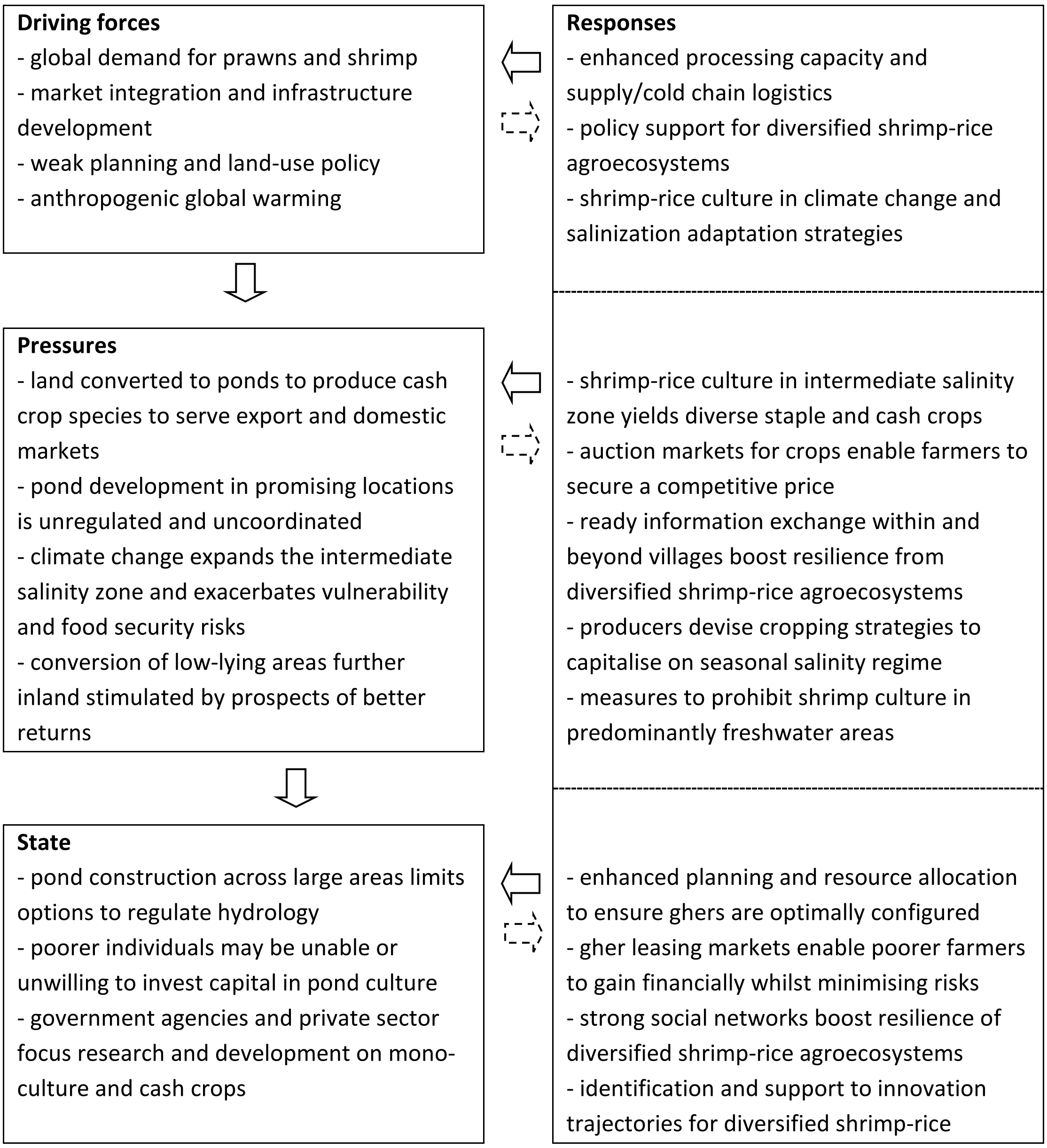
Following the devastation caused to communities and ecosystems in the Indian Sundarbans by cyclone Aila in May 2009 the Department of Irrigation and Waterways (DoIW), Government of West Bengal was engaged in preparing a Detailed Project Report (DPR) for embankment renovation and realignment (Mr Samanta, Secretary, DoIW, personal communication). Ordinarily, the main function of the DoIW is to maintain and renovate the embankments that surround many of the islands in the larger Sundarbans area. Overall there are 3500 km of embankments and the DoIW is responsible for maintaining 3300 km of these, the remainder are under the jurisdiction of *gram panchayats* (locally elected councils). This is a huge undertaking as most of the embankments were constructed around 150 years ago in a rather haphazard manner to prevent the ingress of saline water and make land in the area cultivable. A large area of mangroves was reportedly lost as the result of this reclamation work, whilst natural movement of the river to the east has resulted in a fundamental change to the local hydrology. Mangrove regeneration was included in the post-Aila DPR, the plan being to plant mangrove in front of the rehabilitated embankments to reduce wave heights; the mangrove strip was to extend 30 m from the toe of the embankment. Enactment of the Coastal Regulation Zone Act has attached further importance to development of shrimp-rice farming in North-24-Parganas and South-24-Parganas, notably Gobaria Beel area.

Policies promoting disaster preparedness and relief and rehabilitation plans have been formulated by the Government of Bangladesh. Community involvement is deemed critical to disaster preparedness. Several Bangladeshi aid groups have concluded that without community participation, even well-intentioned disaster relief programmes do little to protect target communities in the long-run. Climate change impacts will include sea-level rise and greater variation in the hydrological regime at the interface of marine and freshwater environments and this may make new areas suitable for shrimp-rice culture. More extreme conditions will, however, equate to greater vulnerability and risks for producers. Community-based adaptation combined with integrated action planning approaches (Ahmed et al., 2014; Bunting et al., 2016) could support shrimp-rice culture development as an appropriate production strategy for brackish water areas. Considering the need to increase aquatic food supplies globally, Muir (2013) noted that better integrated use of land and water resources in coastal areas subject to salinization could enhance options for food production.

3.6. Options to promote wider resilience

Cereal crop monocultures promoted during the Green Revolution ultimately resulted in decreased production of pulses, a staple food for the poor in much of rural Bangladesh and West Bengal. Trends toward larger farms with increased mechanisation result in fewer livelihoods and employment opportunities associated with agriculture and consequently a disconnection with land, water and nature. Rural-urban migration has been a notable feature of the livelihoods perused by younger household members from large parts of rural and coastal Bangladesh and West Bengal, India (Punch and Sugden, 2013). Ultimately the loss of direct dependence on natural resources as a source of livelihoods, accumulation of financial capital and formal schooling can result in the loss of traditional ecological knowledge (Pilgrim et al., 2007).

Drawing on the review presented above, high-level Driving forces and Pressures that have stimulated diversified shrimp-rice agroecosystems are specified in Figure 3. The State of the system and associated Impacts on local communities and environments are summarised. Responses that have or could further enhance social-ecological resilience are specified. Responses can be identified at a range of scales, from strong social networks to strategic changes to coastal area management policies and the preparation of climate change adaptation strategies. Carbon sequestration rates for integrated agriculture-aquaculture systems were estimated at 21.2 t ha^{-1} y^{-1} but it was noted that practices such as pond sediment removal could release greenhouse gases (Ahmed et al., 2017). If carbon sensitive management strategies could be widely instigated, diversified shrimp-rice agroecosystems could bolster blue carbon capture and storage, contributing to climate change mitigation (Ahmed and Glaser, 2016a, 2016b).



- knowledge of culture practices in Bangladesh and India is asymmetric and innovation trajectories have diverged

agroecosystems and promotion of allied Better Management Practices

Impacts
- production from diversified shrimp-rice agroecosystems has stimulated local economic development and bolstered employment and reducing poverty
- diversity of crops produced contributes to nutrition and food security in farming households and local communities, especially for adolescent females and young children
- intensification of management in diversified agroecosystems, not external input use, generates more employment
- enhanced agrobiodiversity contributes to conservation objectives and bolsters resilience to commodity price fluctuations, seasonality, disease outbreaks and natural disasters

Figure 3. DPSIR assessment for diversified shrimp-rice agroecosystems identifying Responses to enhance social-ecological resilience.

Technology adoption by farmers may be motivated by production enhancement (yield and quality), efficiency gains (per unit input, labour or land) and resistance and resilience (to pests, weeds, drought or water-logging). Extension agents and government initiatives and commercial interests might be strong advocates for the adoption of new technologies. Key issues for farmers adopting technology are greater exposure to rising or fluctuating input costs and becoming locked in to debt and repayment cycles. Consequently, this may constrain future innovation, diversification and the transition between alternative cropping and livelihoods strategies. Environmental impacts associated with manufacturing inputs and negative externalities of application on soil health, water quality, biodiversity and ecosystem services must be considered. It was postulated that greater dependence on externalising technology inputs, combined with diminishing social capital, results in loss of natural capital (Bunting et al., 2010) but not all technology is inherently bad (Little and Bunting, 2015).

Test kits constitute a relatively modest investment that could facilitate water quality and disease prevalence monitoring and potentially help optimise input use-efficiency. Development of techniques to close the life-cycle of shrimp in hatcheries and broodstock facilities could help reduce demand for wild broodstock and seed, leading to conservation of wild populations and avoidance of by-catch. Seed from hatcheries could be acclimatized prior to dispatch, tested and certified disease free and potentially vaccinated, thus reducing disease risks and antibiotic use. Information Communication Technologies (ICTs), such as the Livestock Guru (Heffernan and Nielsen, 2007) linked to mobile devices could enhance water management and husbandry skills and promote better disease management, including adoption of effective integrated pest management.

Photovoltaic and wind-powered electricity generation, allowing communities to receive educational and informational radio and television programming and have artificial lighting to permit study could substantially enhance: environmental awareness; knowledge of sustainable aquaculture and agriculture; educational outcomes and life prospects. Shortwave radios could make policing and enforcement of environmental protection and conservation strategies more effective, whilst affording communities an early warning about storms and other dangers. Technologically advanced fishing gear, perhaps incorporating wheels on beam trawls or sonic sounders on nets can reduce by-catch, including that of vulnerable species such as dolphins and turtles. Prospects for the sustainable intensification of agriculture were comprehensively reviewed (Davies et al., 2009). A comparable assessment building on the framework for evaluating sustainable intensification impacts across aquaculture product value chains outlined by Little et al. (in press) could help guide future aquaculture development.

Better Management Practices (BMPs) have emerged as a promising means to transfer knowledge of responsible aquaculture development. The consortium responsible for developing the 'Practical manual on better management practices for tambak farming in Aceh' to guide post-tsunami rehabilitation of shrimp ponds (ADB et al., 2007) was awarded the Word Bank Green Award 2006 (NACA, 2007). The BMPs advocate practical approaches to reducing shrimp health problems: pest eradication with naturally occurring toxins and exclusion of wild juveniles and other organisms that might harbour disease; avoidance of synthetic chemical treatments that may pose animal, environmental and public health risks; stocking active and strong seed, tested for diseases and from well managed nurseries; instigating regular monitoring and recording of shrimp mortalities, and as soon as problems are detected, taking precautionary steps including partial water exchanges and in extreme cases, emergency harvests.

Guidance to farmers on pond preparation and liming and fertiliser application rates was designed to make efficient use of production enhancing inputs. Advice on restricting water exchange and employing minimal pumping to maintain a water depth of 80 cm and compensate for poor water quality, and retaining pond water for a month after a disease outbreak, was aimed at: limiting pumping costs; making efficient use of nutrient and water inputs; minimising disease introductions and transfers to other producers. Conservative shrimp stocking densities and integrated culture of milkfish and seaweed were advocated to: help maintain pond sediment and water quality; avoid adverse environmental impacts; spread financial risks; achieve more regular cash-flows. Bioeconomic modelling was used to evaluate potential returns from shrimp farms in the Mahakam Delta, Indonesia if they were to adopt such BMPs (Bunting et al., 2013) or green-water culture to avoid white spot syndrome virus (Bosma et al., 2012). This assessment method could be used to evaluate the financial sensitivity of diversified shrimp-rice agroecosystems in different contexts.

To counter uncoordinated and unregulated development, enhance production and achieve better management of common property resources Islam et al. (2005) described how the shrimp farming sector in Bangladesh could be reorganised. These authors advocated stricter regulation and reconfiguring the system to produce 1 ha ponds that could be drought under better management practices. It was noted that careful planning and substantial investment would be needed. Appropriate legal instruments and economic, social and ethical assessment would be required to ensure the process was legitimate, equitable and sustainable. Systematic restructuring of the physical area and access arrangements could present opportunities for diversified shrimp-rice expansion in intermediate salinity areas.

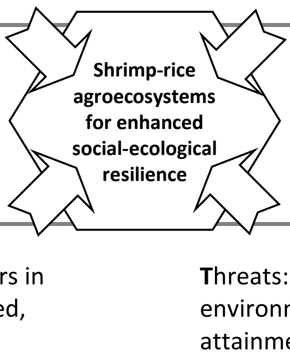
Farmer field schools, cooperatives or business and micro-credit groups could support farming households engaged in shrimp-rice culture in small ponds. These types of investment in social capital have been shown to be critical for efficient information sharing and trust-building (Pretty et al., 2011). A strategy based on awareness-raising and education to ensure local people support conservation measures and adopt environmentally sound practices is needed (Sarkar and Bhattacharya, 2003). Such an approach could have a significant impact on transforming coastal aquaculture in Bangladesh and West Bengal, India ensuring sustainability and resilience are central to future developments. Building on the preceding review, strengths and weaknesses associated with diversified shrimp-rice agroecosystems in Bangladesh and West Bengal, India are summarised in Figure 4. Potential opportunities and threats in the external environment that may govern the spread of shrimp-rice culture more widely and consequently demand further assessment are highlighted.

- prevailing typography and hydrology across large areas suited to shrimp-rice culture
- knowledge of shrimp-rice culture is widespread
- private sector input suppliers and service providers established
- institutions and mechanisms for credit provision established
- education and extension services cover integrated aquaculture-agriculture systems
- national level policies support integrated aquaculture-agriculture systems development

Strengths: existing or potential resources or capability

- inadequate planning and lack of policy support may prevent expansion of shrimp-rice culture in promising areas
- economic and institutional barriers may prevent reconfiguration of existing infrastructure
- failure to counter saline intrusion may force producers to convert to less diverse, high salinity cropping strategies
- sector specific research, development and innovation may undermine synergistic effects and not match producer needs

Weaknesses: existing or potential internal force that could be a barrier to achieving objectives/results



Opportunities: existing or potential factors in the external environment that, if exploited, could provide a competitive advantage

- established markets and value chains with capacity to handle increased supply

Threats: existing or potential force in the external environment that could inhibit maintenance or attainment of unique advantage

- land-use policy and adaptation (climate change, salinization) strategies fail to capitalise on

- international agreements and national policies support responsible aquaculture development	potential benefits of diversified shrimp-rice agroecosystems
- climate change induced hydrological regime shift may extend area for shrimp-rice culture	- irrational objections to converting low-yielding cereal crop land to more productive and financially rewarding diversified shrimp-rice agroecosystems
- evidence that strong social networks and efficient information exchange promote resilience should inform policy and practice to support existing and new producers	- reticence by development agencies to sponsor initiatives involving shrimp culture as it may be perceived as only occurring in a damaging monoculture
- promotion of Better Management Practices from existing systems could aid successful adoption in promising new locations	

Figure 4. SWOT assessment of diversified shrimp-rice agroecosystems development.

4. Conclusions

Diversified shrimp-rice farming has been adopted by specific farming communities on the periphery of the trans-boundary Sundarbans mangrove forest in Bangladesh and West Bengal, India. Diversified shrimp-rice agroecosystems fit with a set of environmental and hydrological factors that occur in these areas. Synergistic ecological processes within shrimp-rice fields lead to more efficient resource use and enhanced production. Reduced inputs of agrochemicals, feeds and fertilisers help minimise impacts on the surrounding environment, whilst the integrated cropping system contributes to enhanced agrobiodiversity. Diversified shrimp-rice agroecosystems produce both cash and staple crops and contribute to economic development, food security and social-ecological resilience.

Outcomes from this review highlight four main policy relevant recommendations:

- shrimp-rice culture should not be promoted in predominantly freshwater areas as transfers of saltwater inland could increase prevailing salinity levels in adjoining areas thus eliminating rice and vegetable cultivation;
- climate change adaptation and coastal realignment programmes should be designed with diversified shrimp-rice agroecosystems in mind;
- communities in areas subject to increased salinization owing to climate change induced hydrological regime changes should be supported in adopting diversified shrimp-rice agroecosystems;

- policy- and decision-makers, government departments, extension agents, service providers and development agencies should be made aware of the diversify of cultured and wild aquatic animals and terrestrial crops (rice and vegetables) produced in diversified shrimp-rice agroecosystems and support the Responses outlined here to promote social-ecological resilience.

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