Aquaculture production in Asia—Resilience towards climate change impacts

Abstract

This study analyzes fresh and brackish water aquacultures—especially carp, tilapia, and shrimp production—in major Asian aquaculture-producing countries. Different indicators have been used, involving dimensions that may be affected by climate change. High diversity is believed to indicate high adaption capacity, while resilience is estimated by known biological properties of each species. The results confirm that China, by far, has the largest diversity of species and values, followed by Bangladesh, Indonesia and Vietnam. Evaluation of the resilience of major species in light of the impacts climate change may have on warming, seawater intrusion and reduced fish meal supply, indicates that shrimp species are more resilient than tilapia, carp and catfish. In general, resilience of aquaculture products in Asia seems to be high, and the aquaculture production could adapt to climate change impacts by proper modifications in farming systems and infrastructure facilities in the future.

Key words: Aquaculture, diversity, climate change, vulnerability, resilience

Introduction

The world's aquaculture production is dominated by Asian countries. China, India, Vietnam, Indonesia and Bangladesh are the world's major aquaculture producers and the Asian share of global farmed fish production in terms of quantity is close to 90% (Anon., 2018a). Aquaculture is also becoming increasingly more important for food supply, food security and income generation in Asian countries. Millions of people in Asia depend on aquaculture, either directly or indirectly (Eide et al., 2011). Hence, the sustainability of the Asian aquaculture sector is a matter of global importance.

Fish farming has been an integral part of Asian agriculture since ancient times. However, over the last 50 years the aquaculture sector in Asia has experienced a tremendous growth (see, for example, De Silva and Davy, 2010). Rapid expansion has, in particular, been driven by technological development and new market opportunities (Dey et al., 2005a; Kumar & Engle, 2016). The total Asian aquaculture production in 2016 (excluding aquatic plants and non-food products) was about 72 million tons (Anon., 2018a). The ten biggest producers in Asia are China, India, Indonesia, Vietnam, Bangladesh, Myanmar, Thailand, Philippines, Japan and Republic of Korea, listed according to production levels in 2016 (Anon., 2018a).

The possible impact that climate change may have on Asian aquaculture production, and how this may affect the sustainability of the sector, is increasingly becoming a concern (Vivekanandan, 2010). This includes potential effects on aquaculture production by sea level and temperature rise, changes in rainfall pattern, and possible increases in extreme weather events (De Silva & Soto, 2009). Although climate change may affect aquaculture production both positively and negatively, either directly or indirectly, and in different degrees in varying regions (Easterling et al., 2007; Handisyde, Ross, Badjeck & Allison, 2006; De Silva & Soto, 2009; Porter et al., 2014), all environmental changes represent challenges for the existing aquaculture industries. A number of reasons—including high population growth, high poverty rate, followed by natural resources degradation and food insecurity—may indicate that South Asia is among the most vulnerable regions when it comes to climate change impacts (Sivakumar & Stefanski, 2010).

The aim of this study is to investigate how specific factors within aquaculture production in selected Asian countries may be affected by climate change. This was done by focusing on the vulnerability and resilience of current aquaculture production systems and species toward possible climate change impacts.

Materials and Methods

Data material and industry characteristics

In Japan and the Republic of Korea, the aquaculture sector is totally dominated by marine species. The remaining 10 largest producers are included in this study. In addition, Sri Lanka is included as a representative of the emerging aquaculture industry in other Asian countries. Hence, the selected nine aquaculture-producing countries of this study are *China, India, Indonesia, Vietnam, Bangladesh, Myanmar, Thailand, Philippines,* and *Sri Lanka*, listed according to production quantities.

More than 100 different species are cultivated in Asian countries (Anon., 2017a); 97 of them are represented in this study (see Table 1). These species include finfishes, mollusks, crustaceans, and other aquatic invertebrates. By volume, finfish species (mainly carp, tilapia and catfish) dominate the Asian-farmed fish production. In 2016, finfish production from inland aquaculture was about 44 million tons, more than 60% of the total Asian-farmed fish production (Anon. 2018a). As seen from Figure 1, carp and catfish dominate in terms of both volume and value in the investigated countries, followed by tilapia (in terms of volume) and shrimp (in terms of value).

The diversity of the aquaculture sector in the nine countries is demonstrated by Table 1 and Figures 1 and 2 in terms of the variety of species. However, the diversity also includes a range of different production systems and aquaculture techniques ranging from extensive to intensive methods and from small to large scale (Wang et al., 2014; Dey et al., 2005a; Dey et al., 2000; Dey et al., 2005b). Freshwater aquaculture (inland aquaculture) is dominant throughout the region. Different production systems for fresh and brackish water aquacultures include *ponds*, *cages*, *pens*, *net enclosures*, *lakes*, *tanks*, and *paddy fields*. Among these, ponds are the major farming environment used for inland aquaculture in Asia (Dey et al., 2005a; Dey et al., 2005b). Natural water reservoirs, dams and mangrove ecosystems are widely used for aquaculture. Depending on inputs and degrees of production control, aquaculture systems are classified into *extensive*, *semi-intensive*, and *intensive* systems.

(Figure 1 has to be inserted here)

Extensive and semi-intensive systems represent traditional methods with limited production control. Farming takes place in natural reservoirs or earthen ponds where there is no or negligible use of artificial feeds. In contrast, intensive farming takes places under controlled farming conditions (in ponds, pens, cages or land-based tanks), which require skilled management procedures (proper feed supply, disease control, energy sources, etc.).

In the early history of aquaculture development, extensive and semi-intensive methods of farming were carried out by conventional techniques. As technology has improved, farming systems gradually have developed into intensive industries in many countries. Both mono- and polyculture production systems are widely used (Dey et al., 2005a). Also, integrated fish farming systems (systems of producing fish in combination with livestock rearing or crop cultivation) have successfully been employed (De Silva & Davy, 2010). Examples of integrated farming systems include gher (prawn-fish-rice) farming in Bangladesh, and rice-fish farming in China and the Philippines (Rahman, Barmon, & Ahmed, 2011; Wang et al., 2014).

(Table 1 has to be inserted here)

(Figure 2 has to be inserted here)

There is a considerable amount of subsistence and artisanal small-scale farming in many Asian countries today. However, the majority of commercial aquaculture farms operating in the largest aquaculture-producing countries are either medium or large-scale, mainly targeting international markets. In several Asian countries, the aquaculture sector is a well-developed industry, while in some countries, including Sri Lanka and Bangladesh, the sector still requires financial and technical support for development.

(Table 2 has to be inserted here)

The logarithmic scale of the vertical axes in Figure 1 and the upper row of Figure 2 indicate clearly how the aquaculture production has experienced exponential growth in these countries over the given period. It is also evident from the lower row of Figure 2 that the growth in the sector outspans the population growth in all the nine countries, as the produced quantity-per-capita shows exponential growth. In terms of the sectors' economic contribution, the picture shows more variation, although in general the sectors' share of each country's GDP is fairly stable or slightly declining. In cases of decline, this indicates that the general economic growth outspans the economic growth in the aquaculture sector (as, for example, in the cases of China, Thailand and Sri Lanka).

(Table 3 has to be inserted here)

Table 2 presents the 38 most important farmed species/families in terms of production quantity. The listed species represent more than 87% of a total of 51 million tons produced by the nine countries in freshwater and brackish water in 2016. One quarter of this production is composed of two single carp species, *Ctenopharyngodon idellus* and *Hypophthalmichthys molitrix*. Other key numbers of the nine countries are found in Table 3, where produced volume-per-capita and per-land-area are presented in addition to production value-per-GDP.

Figure 3 reveals important differences between the selected nine countries. For China, India and Myanmar, carp species dominate volume- and value-wise; for the latter, the volume of carp production makes up 84% of the total freshwater and brackish water aquaculture production. Carp production is, however, almost absent in the Philippines and Thailand. In

Thailand, shrimp species dominate, while catfish production totally dominates the Philippine production (72% of the total volume). Economically, shrimp species constitute the largest value shares in the Philippines, Sri Lanka, Thailand and Vietnam.

(Figure 3 has to be inserted here)

However, these figures do not tell the full story about production diversity in the countries. The low relative production of carp species in Sri Lanka, for example (14% of total production value in the country), does come from production of nine different carp species.

Of the freshwater and brackish water productions, 90% are freshwater (as of 2016), while only some high-valued species (e.g. *Penaeus* and *Scylla* species and a few others) are grown in brackish water environments. The brackish water production also includes some tilapia species, which is an indication of the tolerance such species have toward different environmental conditions. By and large, however, the production of tilapia takes place in freshwater.

Methods

Data on global and regional climate projections on changes in temperatures, precipitation levels, sea level and ocean acidity conditions, have been collected from Reilly et al. (2015) and the latest AR5 IPCC report (Rhein et al., 2013). The expectation is an increase in the global mean surface temperature in the range of 1.9°C to 2.6°C by 2050, and an increase in the global mean precipitation in the range from 3.9% to 5.3% by 2050 (Reilly et al., 2015). Quantitative data on changes in precipitation level and sea level rise for the Asian region are not yet available. Therefore, available qualitative data have been used in this study.

To examine the degree of sensitivity of a species to the projected climate change consequences, information on biology, feeding habits, environmental requirements for better growth and tolerable ranges (water temperature, pH, salinity, and oxygen-levels) of the selected main species have been collected from various sources, including FAO's Fishbase database (Froese & Pauly, 2016). This information is summarized in Table A1 (Appendix).

This study adapts the IPCC definition of *vulnerability*. Vulnerability is the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including variability and extremes (Parry, Canziani, Palutikof, Linden & Hanson, 2007). *Resilience* is the capacity of a system to absorb disturbance and reorganize while undergoing changes, and still essentially retain the same function, structure, identity and feedback (Walker, Holling, Carpenter & Kinzig, 2004). It is conceptualizsed as a function of exposure, sensitivity and adaptive capacity by Brugere and De Young (2015): Vulnerability = *Exposure* + *Sensitivity – Adaptive capacity*.

Vulnerability and resilience of major species have been assessed by expert judgments on the basis of available specific and general information (Table 4, a–c). This assessment takes into account three different factors which may be affected by climate change: *higher temperatures*, *sea level rise* and *less- and more expensive fish feed* for the aquaculture industry. Sea level rise may also increase the occurrences of sea level intrusion. The rationale behind including fish feed as one particular factor of climate change also includes the possible indirect effects through changes in markets.

Diversified farming is expected to be preferable in adapting to changes in environmental constraints of aquaculture production. Species diversity indices are widely used to describe species richness. In the study, the Shannon-Wiener diversity index (known as the H-function) has been employed as a measure of diversity in the aquaculture production. Both quantity and value diversities within each country over the investigated period are measured, including the various species in the production of data on main species groups (carp, catfish, tilapia, gourami, shrimp, crab, cray fish and others). The quantity diversity is considered to be a food security resilience indicator, while the value diversity reflects income resilience. The H-function is given by:

$$H = \sum_{i=1}^{s} P_i \cdot \ln P_i$$

where P_i is the quantity or value of variable i and s is the total number of variables in the sample.

The annual diversity indices have been fed into a cluster analysis to identify overall distances between the producing countries in terms of aquaculture production and income diversities during the period. By combining the vulnerability assessment results and diversity indices for each country, the resilience of major species productions is discussed in following section.

Our assumption is that different combinations of aquaculture species and production practices are reflected in varying vulnerabilities toward climate change impacts. We expect some aquaculture species and farming systems to be more resilient and to have better adapting strategies than others do.

Results

The results show that China, by far, has the largest diversity of species and values, followed by Bangladesh, Indonesia and Vietnam. As shown in Figure 4, all the countries show a high diversity and variety in terms of species. The difference between diversity by quantity and value indicates that carp products are cheap compared with shrimp.

We have not taken into consideration domestic consumption and export in this study. However, export products are more vulnerable in the sense that sales depend on access to markets abroad. To a large degree, export can be said to be related to shrimp fisheries (especially in Philippines, Thailand and Vietnam), while carp and tilapia farming is only for domestic consumption.

(Figure 4 has to be inserted here)

(Figure 5 has to be inserted here)

The dendrogram plots in Figure 5 show two distinct clusters: one with China, Bangladesh, India, Myanmar and Sri Lanka; the other with Vietnam, Philippines, Thailand and Indonesia, for 2016. Sri Lanka and Myanmar have moved from last to first over the last few decades, due to the rise in their levels of aquaculture industry development. One could expect to find China as a single outlier in this figure but that is not the case. China certainly is the largest and most important producer, but is very similar to other Asian countries both in terms of quantities produced and the diversity of their production.

(Figure 6 has to be inserted here)

As seen from Figure 6, warming does not constitute a real hazard for the species. It is more a matter of climate changes driven by changes in temperature. These changes, however, are expected to happen at a moderate speed compared with the dynamic of the aquaculture industry.

Tables 4a–4c show specific species and their vulnerability in terms of three dimensions: Warming, seawater intrusion and reduced supply of fish meal. A spider chart placed at each species illustrates the change from an idealized (current, dashed) situation to a warmer (solid lines) situation along the three axes. The total effect is calculated as the percentage difference between the two areas (dashed figure and solid line figure). When we consider the four major species, obviously shrimp aquaculture is more resilient than tilapia, carp, and catfish by this number; the latter two species are less resilient toward the three measured factors. Other species such as gourami, crab and crayfish are also less resilient toward the three measured factors.

As water is a crucial factor in aquaculture production, changes in rainfall pattern may affect farming systems either positively or negatively. Water scarcity is expected to be a major challenge in most parts of the Asian region (Hijioka et al., 2014). Water scarcity in the future, therefore, might threaten aquaculture production in the region if water management is not improved. On the other hand, an increase in annual rainfall will favor growth, given properly managed aquaculture systems with regard to nutrition and diseases. Availability of water provides opportunities for building ponds at new locations and farming aquatic species in natural water bodies.

(Table 4a has to be inserted here)

(Table 4b has to be inserted here)

(Table 4c has to be inserted here)

Discussion and conclusion

The aquaculture industry in the nine countries separates into two main clusters (Figure 5). One (China, Bangladesh, India, Myanmar and Sri Lanka) is characterized by high diversities and dominance of carp species (Figure 4). The other cluster is less diverse and shrimp species dominate. Diversity is believed to be positively correlated to resilience, and shrimp production is found to be more resilient than other types of production, given the dimensions studied here. The broad picture, therefore, is that Asian aquaculture production is fairly resilient toward the climate change effects studied here. This does not mean that there will not be changes in the industry over time, as such changes are taking place all the time, making high diversity an important factor.

Economically, the industry is more important in Vietnam, Bangladesh, Myanmar and China than in the other countries (Table 3), and as such, these countries may be said to be more vulnerable to changes in the industry. Bangladesh and Vietnam, followed by China, are using the largest share of land areas for aquaculture production (Table 3), possibly indicating a higher vulnerability than the other countries. However, these countries, together with Indonesia, have the highest diversity in their production, covering a large number of species with different properties (Figure 4). None of these countries depend heavily on only one important species.

In the lower end of diversity we find India and Myanmar, both dominated by carp production, which appears to be the most vulnerable species toward climate change. This could indicate a higher vulnerability for climate change in these two countries. Sri Lanka is close to being in the same situation, while the more resilient shrimp production dominates in Thailand and the Philippines, the other two countries with relatively low diversity (Figure 4).

The countries most involved in the world trade of aquaculture products seem to be less vulnerable, not because of their export, but because their products are more resilient toward climate change impacts. However, the main conclusion is that the overall resilience of aquaculture products in Asia seems to be high, perhaps higher than expected. There are several reasons for this. The high variability in production methods and species are perhaps the most prominent. Another reason is that many of the species in question are very robust and resilient. This is particularly the case for the shrimp species, but also for others. It should, however, be noted that diseases may change the picture, in particular with respect to shrimp aquaculture. In this study, we have not considered a higher risk of diseases as one isolated factor but we know from previous experience that the severity of such incidents is a function of diversity and size of the production.

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Appendix

Table A1: Feeding habit and environmental requirement of ten main carp, catfish, tilapia and gourami species cultured in the Asian region. S refers to stressful and L lethal. Data given in parenthesis are ideal ranges of requirements for better growth.

Species	Feeding habit	Temp. (°C)	pH	Salinity (ppt)	O_2 level (ppm)	Protein need (%)
Grass carp[1,2] *Ctenopharyngodon idellus*	Herbivorous	0-38 (22-30)		10		(28-35)
Silver carp[2,3] *Hypophthalmichthys molitrix*	Filter feeders	6-28				(28-35)
Common carp[2,4,5] *Cyprinus carpio*	Detritivore / Omnivorous	3-35 (23-30)	7.0 - 7.5	10.5 (0.5-4.5)		(28-35)
Bighead carp[6,7] *Hypophthalmichthys nobilis*	Filter feeders	0.5 – 38 (22-30)		7		
Crucian carp[8,9] *Carassius carassius*	Detritivore / Omnivorous	2-22		20 (8)		
Catla[2,10] *Catla catla*	Filter feeders / Planktophagous	15-41 (31-33)				(28-35)
Roho labeo[2,10] *Labeo rohita*	Omnivorous	14-42 (31-33)				(28-35)
Wuchange beam[11] *Megalobrama amblycephala*	Herbivorous	10-20				
Black carp[12] *Mylopharyngodon piceus*	Carnivorous	0-40	7.5 8.5			
Mrigal carp[10,13] *Cirrhinus mrigala*	Detritivore / Herbivorous	13-42 (31-33)		High tolerance		(30- 45)
Striped catfish[14,15] *Pangasianodon hypophthalmus*	Omnivorous	22-26	6.5 - 7.5			(29-33)
Amur catfish[11] *Silurus asotus*	Carnivorous	5-25				
Yellow catfish[16] *Pelteobagrus fulvidraco*	Carnivorous	16-25				
Channel catfish[17,18] *Ictalurus punctatus*	Carnivorous	0-38 (29-36)	6 - 8	0-11 (above 4)		25-55 (36-40)
Nile tilapia[19,20,21] *Oreochromis niloticus*	Omnivorous	14-34 (26-30)	5-10 (6-9)	Up to 15		(26-30)
Mozambique tilapia[21,22] *Oreochromis mossambicus*	Omnivorous	17-35 (29-31)	5-10 (6-9)	High tolerance		(26-30)
Giant gourami[23,25] *Osphronemus goramy*	Herbivorous	20-30	6.5-8.0	12 (0-4)		(34)
White leg shrimp[26,27] *Penaeus vannamei*	Carnivorous	15-35 (28-32)	7.0-9.0 (7.4-7.8)	0.5- 45 (7-34)	<1.5 (L) (5.0-9.0)	(20-35)
Giant tiger shrimp[26, 28,29,30] *Penaeus monodon*	Omnivorous	18-34.5 (28-32)	(7.8-8.2)	5-45 (29-34)	(>4)	(36-42)
Oriental river prawn[31,32,33] *Macrobrachium nipponense*	Omnivorous	6.5-33 (26-32)	(8.4-8.5)	0-20 (14)	(4.5)	
Giant river prawn[34,35,36,37] *Macrobrachium rosenbergii*	Omnivorous	12-35 (28-31)	>9.5 (S) (7-8.5)	0-15 (<10)	2 (S) (3-7)	13-25 (25-30)
Kuruma prawn[38] *Penaeus japonicus*	Carnivorous	(24-30)	(7.0-9.0)	30-35	> 4.0	
Fleshy prawn[39,40,41] *Penaeus chinensis*	Omnivorous	18-33 (28-31)		15-40 (30)		
Banana prawn[42,43,44] *Penaeus merguiensis*	Omnivorous	20-34 (28-33)		(30-35)		

Indian white prawn[45] *Penaeus indicus*	Omnivorous	18-34.5 (28)	7.5-8.5	5-50	30-43	30-43
Red swamp crawfish[46,47] *Procambarus clarkia*	Omnivorous	13-32 (20-25)		Up to 30	15-20	15-20
Chinese mitten crab[48] *Eriocheir sinensis*	Omnivorous	18- 30 (28–30)		0.5-25		

[1]Shireman and Smith, 1983; [2]Jhingran and Pullin 1985; [3]Skelton, 1993; [4]Kottelat and Freyhof, 2007; [5]Wang et al., 1997; [6]Li et al., 1990; [7]Anon. 2019a; [8]Riel and Baensch, 1991; [9]Kucuk, 2013; [10]Das et al., 2004; [11]Baensch and Riehl, 1997; [12]Nico et al., 2005; [13]Anon. 2019b; [14]Phuc et al., 2017; [15]Anon.2019c; [16]Baensch and Riehl, 1991; [17]Suja et al., 2009; [18]Anon. 2019d; [19]Trewavas, 1983; [20]Azaza et al., 2008; [21]Popma and Masser 1999; [22]Trewavas, 1982; [23]Ebrahimi et al., 2011; [24]Azrita and Syandri, 2018; [25]Phuong et al., 2015; [26]Briggs et al., 2005; [27]Wyk and Scarpa 1999; [28]Anon, 2017b; [29]Ern et al., 2015; [30]Anon. 2007; [31]Gholamali et al., 2011; [32]Kutty and Weimin, 2010; [33]Hongtuo and Jin 2018; [34]New, 2002; [35]Ern et al., 2014; [36]Chand et al., 2015; [37]D'Abramo and New, 2000; [38]Anon. 2006; [39]Hewitt and Ducan, 2001; [40]Chen et al., 1992; [41]Tian et al., 2004; [42]Staples and Heales, 1991; [43]Zacharia and Kakati, 2004; [44]Hoang et al., 2002; [45]Anon. 2019e; [46]Chen et al., 1995; [47]McAlain and Romaire, 2009; [48]Normant et al., 2012.

Tables

Table 1. Species included in the study grouped as referred to in text and figures. These include all freshwater and brackish water farmed species of the selected nine countries according to the FAO statistics (*FishBase*), excluding aquatic plants and non-food products.

Carp	**Tilapia**	**Others**
Carassius spp	*Oreochromis aureus x O. niloti*	*Puntius spp*
Labeo dussumieri	*Oreochromis mossambicus*	*Monopterus albus*
Hypophthalmichthys nobilis	*Oreochromis niloticus*	*Notopterus*
Mylopharyngodon piceus	*Oreochromis (=Tilapia) spp*	*Protosalanx hyalocranius*
Catla		*Anabas testudineus*
Cyprinus carpio	**Gourami**	*Chitala*
Cyprinidae	*Osphronemus goramy*	*Osteichthyes*
Ctenopharyngodon idellus	*Trichogaster spp*	*Channa marulius*
Leptobarbus hoeveni	*Helostoma temminckii*	*Eleotridae*
Osteobrama belangeri	*Trichogaster pectoralis*	*Channa micropeltes*
Cirrhinus mrigala		*Anguilla japonica*
Cirrhinus molitorella	**Shrimp and Prawns**	*Hilsa kelee*
Osteochilus hasselti	*Acetes japonicus*	*Notopterus spp*
Labeo calbasu	*Penaeus merguiensis*	*Micropterus salmoides*
Labeo rohita	*Penaeus stylirostris*	*Siniperca chuatsi*
Hypophthalmichthys molitrix	*Penaeus chinensis*	*Oxyeleotris marmorata*
Rohtee ogilbii	*Palaemonidae*	*Marine fishes*
Megalobrama amblycephala	*Macrobrachium rosenbergii*	*Miscellaneous aquatic animal products*
	Penaeus monodon	*Miscellaneous aquatic animals*
Catfish	*Penaeus indicus*	*Molluscs*
Clarias gariepinus x C. macroc	*Penaeus japonicus*	*Systomus sarana*
Silurus asotus	*Metapenaeus spp*	*Piaractus brachypomus*
Hemibagrus nemurus	*Macrobrachium malcolmsonii*	*Misgurnus anguillicaudatus*
Ictalurus punctatus	*Macrobrachium nipponense*	*Hypomesus olidus*
Leiocassis longirostris	*Penaeus spp*	*Oncorhynchus mykiss*
Siluroidei	*Macrobrachium spp*	*Anguilla spp*
Pangasius spp	*Metapenaeus monoceros*	*Salmonoidei*
Clarias batrachus	*Penaeus vannamei*	*Barbonymus gonionotus*
Heteropneustes fossilis		*Channa argus*
Pangasianodon hypophthalmus	**Crab and Crayfish**	*Channa spp*
Clarias spp	*Eriocheir sinensis*	*Channa punctata*
Wallago attu	*Scylla paramamosain*	*Channa striata*
Pelteobagrus fulvidraco	*Scylla serrata*	*Acipenseridae*
	Brachyura	
	Scylla olivacea	
	Portunus spp	
	Procambarus clarkii	
	Portunidae	
	Cherax destructor	

Table 2. Main freshwater and brackish water aquaculture species (except for species represented in the group *others* in Table 1) and the total production quantities of these by the nine countries in 2016. All numbers are given in million tons produced.

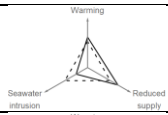
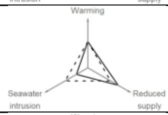
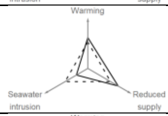
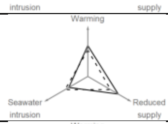
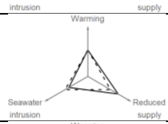
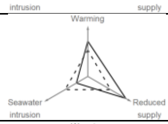
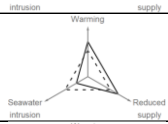
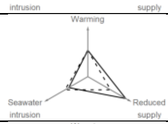
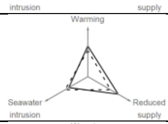
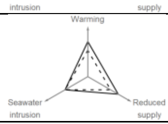
Carp	
Ctenopharyngodon idellus	5.972
Hypophthalmichthys molitrix	5.059
Cyprinus carpio	4.219
Hypophthalmichthys nobilis	3.493
Carassius spp	3.005
Catla	2.927
Labeo rohita	1.780
Megalobrama amblycephala	0.826
Mylopharyngodon piceus	0.632
Cirrhinus mrigala	0.431
Cyprinidae	0.429
Osteochilus hasselti	0.041
Labeo calbasu	0.025
Catfish	
Pangasius spp	1.675
Clarias spp	0.900
Pangasianodon hypophthalmus	0.514
Silurus asotus	0.453
Pelteobagrus fulvidraco	0.417
Ictalurus punctatus	0.286
Clarias gariepinus x C. macroc	0.112
Siluroidei	0.090
Leiocassis longirostris	0.025
Tilapia	
Oreochromis niloticus	2.921
Oreochromis (=Tilapia) spp	0.673
Oreochromis aureus x O. niloti	0.466
Oreochromis mossambicus	0.036
Gourami	
Osphronemus goramy	0.153
Shrimp and Prawn	
Penaeus vannamei	3.327
Penaeus monodon	0.637
Macrobrachium nipponense	0.273
Macrobrachium rosenbergii	0.227
Penaeus spp	0.178
Penaeus japonicus	0.056
Palaemonidae	0.041
Penaeus chinensis	0.039
Penaeus merguiensis	0.025
Crab and Grayfish	
Procambarus clarkii	0.852
Eriocheir sinensis	0.812

Table 3. Population size, gross domestic products (GDPs) and how these figures (in addition to each country's land area) relate to aquaculture production and value of the nine countries. All values are 2014 figures obtained from Anon. (2018b) and FAO's *FishBase* statistics. Only freshwater and brackish water aquaculture production is considered.

Country	Population (mill.)	GDP per capita (US$/year)	Aquaculture volume per capita (kg/year)	Aquaculture value in percent of GDP	Aquaculture volume in tons per km^2 land area
Bangladesh	156.38	1,086.81	12.514	2.807	13.590
China	1,364.77	7,590.02	22.468	1.030	3.195
India	1,291.78	1,581.51	3.774	0.527	1.483
Indonesia	249.56	3,491.93	14.649	0.898	1.919
Myanmar	49.51	1,203.84	18.264	2.498	1.337
Philippines	99.77	2,872.51	3.568	0.373	1.187
Sri Lanka	21.56	3,794.89	1.586	0.088	0.521
Thailand	70.57	5,977.38	9.888	0.591	1.360
Vietnam	91.56	2,052.32	34.328	4.117	9.537

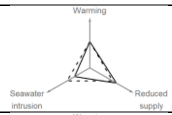
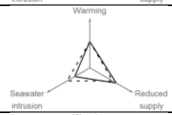
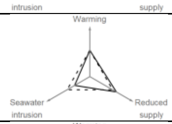
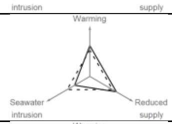
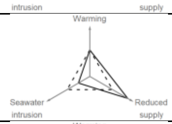
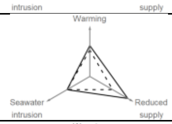
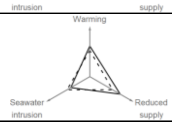
Table 4a: Evaluation of resilience and vulnerability of carp species toward expected consequences of climate change. The heuristic evaluation is based on expert knowledge as it appears in scientific literature, evaluated with a scale of five stages. The mid stage representing the normal situation and the evaluation of future resilience/vulnerability is related to this. Grey

cells represent the evaluations, the lighter grey represents farming in coastal area using extensive methods.

Shrimp, crayfish and crab species		Resilience → ← Vulnerability					Spider chart	Total effect (%)
Grass carp	Warming			■	■			
Ctenopharyngodon idellus	Seawater intrusion	▒	■					-6
	Reduced fishmeal supply				■			
Silver carp	Warming		■	■	■			
Hypophthalmichthys molitrix	Seawater intrusion	▒	■					-17
	Reduced fishmeal supply				■			
Common carp	Warming			■	■			
Cyprinus carpio	Seawater intrusion	▒	■					-6
	Reduced fishmeal supply				■			
Bighead carp	Warming		■	■				
Hypophthalmichthys nobilis	Seawater intrusion				■			21
	Reduced fishmeal supply		■	■	■			
Crucian carp	Warming		■	■	■			
Carassius carassius	Seawater intrusion		■	■				9
	Reduced fishmeal supply				■			
Catla	Warming				■			
Catla catla	Seawater intrusion	▒	■					24
	Reduced fishmeal supply					■		
Roho labeo	Warming				■			
Labeo rohita	Seawater intrusion	▒	■					4
	Reduced fishmeal supply				■			
Wuchange beam	Warming		■	■	■			
Megalobrama amblycephala	Seawater intrusion		■					30
	Reduced fishmeal supply					■		
Black carp	Warming			■	■			
Mylopharyngodon piceus	Seawater intrusion		■	■				21
	Reduced fishmeal supply				■			
Mrigal carp	Warming				■			
Cirrhinus mrigala	Seawater intrusion			■				48
	Reduced fishmeal supply				■			

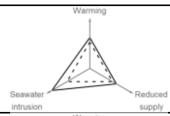
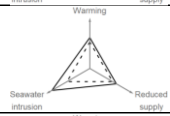
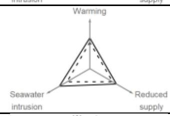
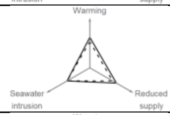
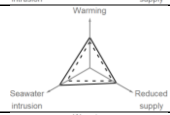
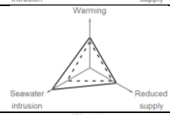
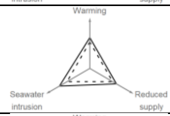
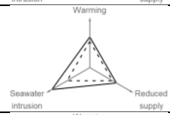
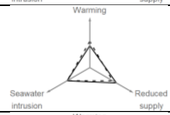
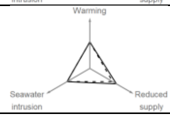
Sources: Anon. 2019a; Anon. 2019b; Baensch and Riehl, 1997; Das et al., 2004; Jhingran and Pullin 1985; Kottelat and Freyhof, 2007; Kucuk, 2013; Li et al., 1990; Nico et al., 2005; Riel and Baensch, 1991; Shireman and Smith, 1983; Skelton, 1993; Wang et al., 1997.

Table 4b: Evaluation of resilience and vulnerability of carp species toward expected consequences of climate change. The heuristic evaluation is based on expert knowledge as it appears in scientific literature, evaluated with a scale of five stages. The mid stage representing the normal situation and the evaluation of future resilience/vulnerability is related to this. Grey cells represent the evaluations, the lighter grey represents farming in coastal area using extensive methods.

Catfish, tilapia and gourami species		**Resilience → ← Vulnerability**	**Spider chart**	**Total effect (%)**
Stripted catfish *Pangasianodon hypophthalmus*	Warming Seawater intrusion Reduced fishmeal supply			-13
Amur catfish *Silurus asotus*	Warming Seawater intrusion Reduced fishmeal supply			-13
Yellow catfish *Pelteobagrus fulvidraco*	Warming Seawater intrusion Reduced fishmeal supply			-13
Channel catfish *Ictalurus punctatus*	Warming Seawater intrusion Reduced fishmeal supply			-3
Nile tipia *Oreochromis niloticus*	Warming Seawater intrusion Reduced fishmeal supply			0
Mozambique tilapia *Oreochromis mossambicus*	Warming Seawater intrusion Reduced fishmeal supply			59
Giant gourami *Osphronemus goramy*	Warming Seawater intrusion Reduced fishmeal supply			21

Sources: Anon. 2019c; Anon. 2019d; Azaza et al., 2008; Azrita and Syandri, 2018; Baensch and Riehl, 1991; Ebrahimi et al., 2011; Phuc et al., 2017; Phuong et al., 2015; Popma and Masser 1999; Suja et al., 2009; Trewavas, 1982; Trewavas, 1983.

Table 4c: Evaluation of resilience and vulnerability of carp species toward expected consequences of climate change. The heuristic evaluation is based on expert knowledge as it appears in scientific literature, evaluated with a scale of five stages. The mid stage representing the normal situation and the evaluation of future resilience/vulnerability is related to this. Grey cells represent the evaluations.

Shrimp, crayfish and crab species		Resilience → ← Vulnerability	Spider chart	Total effect (%)
White leg shrimp *Penaeus vannamei*	Warming Seawater intrusion Reduced fishmeal supply			75
Giant tiger prawn *Penaeus monodon*	Warming Seawater intrusion Reduced fishmeal supply			75
Oriental river prawn *Macrobrachium nipponense*	Warming Seawater intrusion Reduced fishmeal supply			49
Giant river prawn *Macrobrachium rosenbergii*	Warming Seawater intrusion Reduced fishmeal supply			23
Kuruma prawn *Penaeus japonicus*	Warming Seawater intrusion Reduced fishmeal supply			49
Fleshy prawn *Penaeus chinensis*	Warming Seawater intrusion Reduced fishmeal supply			75
Banana prawn *Penaeus merguiensis*	Warming Seawater intrusion Reduced fishmeal supply			49
Indian white prawn *Penaeus indicus*	Warming Seawater intrusion Reduced fishmeal supply			75
Red swamp crawfish *Procambarus clarkia*	Warming Seawater intrusion Reduced fishmeal supply			-1
Chinese mitten crab *Eriocheir sinensis*	Warming Seawater intrusion Reduced fishmeal supply			11

Sources: Anon, 2017b; Anon. 2006; Anon. 2019e; Anon. 2007; Briggs et al., 2005; Chand et al., 2015; Chen et al., 1992; Chen et al., 1995; D'Abramo and New, 2000; Ern et al., 2014; Ern et al., 2015; Gholamali et al., 2011; Hewitt and Ducan, 2001; Hoang et al., 2002; Hongtuo and Jin 2018; Kutty and Weimin, 2010; New, 2002; [47]McAlain and Romaire, 2009; Normant et al., 2012; Staples and Heales, 1991; Tian et al., 2004; Wyk and Scarpa 1999; Zacharia and Kakati, 2004.

Figure captions

Figure 1. Total volume and value of freshwater and brackish water aquaculture production in the nine selected countries (Bangladesh, China, India, Indonesia, Myanmar, Philippines, Sri Lanka, Thailand and Vietnam) 1990-2016. Note the logarithmic scale on the vertical axes. Each group includes species as shown in Table 1.

Figure 2. The upper row displays total volume and value of freshwater and brackish water aquaculture production distributed on the nine selected countries (Bangladesh, China, India, Indonesia, Myanmar, Philippines, Sri Lanka, Thailand and Vietnam) 1990-2016. The lower row shows the same figures related to population size and gross domestic product (GDP) of the given country and year. Note the logarithmic scale on the vertical axes. Population and GDP data is obtained from Anon. (2018b) (1990-2014) and aquaculture production data from FAO's *FishBase* statistics (1990-2016).

Figure 3. Volume and value composition of freshwater and brackish water aquaculture production in the nine selected countries in 2016, separated of groups as defined in Table 1. The numbers give the percentwise production (in quantity and value) within each country.

Figure 4. Aquaculture diversity measured by the 2016 production figures distributed on countries.

Figure 5. Cluster development over time, based on the diversity measure displayed in Figure 4. The figure to the left is a direct cluster of Figure 4, while the two figures to the right display the years ahead of this situation. Note that the distance escalates by longer time-frame, hence the seemingly closer relationship for example between China, India and Bangladesh in the right hand figure is a consequence of larger scale, rather than a real close relationship

Figure 6. The highlighted part of each horizontal bar above indicates ideal temperature ranges for best growth while the whole range of the bar gives the thermal tolerable range of each species. Two black vertical line at 20 and 30ºC indicate assumed upper and lower level of mean ambient temperature range in the region, while the lighter red vertical bar indicates possible increase in the upper temperature level by 2050 (Reilly et al., 2015).