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Future scenarios of fish supply and demand for food and nutrition security in Bangladesh: An analysis with the AsiaFish model

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ABSTRACT

Bangladesh has made significant progress in social and economic development in recent years, but micronutrient deficiencies and poor dietary diversity remain a significant challenge. This paper developed five scenarios to explore futures of fish supply-demand in Bangladesh using the AsiaFish model, with special emphasis on the role of fish in macronutrient and micronutrient supply to address the nation's malnutrition and nutrition security challenges. A business-as-usual (BAU) scenario followed historical trends for exogenous variables used in the model. The four alternative scenarios explored: the implications of increase productivity of farmed tilapia, pangasius and rohu carp (AS1); improvements in the quality of feeds (AS2); disease outbreak in farmed shrimps and prawns (AS3); and climate change impacts (AS4). The BAU scenario indicates that aquaculture growth will be a prominent contribution to increasing total fish supply and demand and fish exports to 2040. Apart from the scenarios that are favourable to aquaculture sector development, other alternative scenarios highlighted the lower growth rate of capture fisheries and aquaculture compared to BAU, resulting in declining in per capita fish consumption, fish exports and nutrient supply from fish as a consequence. Increased availability of aquaculture fish can slightly compensate for the lower growth of capture fisheries in term of their nutrition quality and dietary diversity, particularly for poor consumers. Policies towards sustaining fisheries and a nutrition-sensitive approach to aquaculture is recommended as both capture fisheries and aquaculture are essential for sustaining healthy and nutritious diets in Bangladesh.

1. Introduction

Over the last four decades, fisheries and aquaculture systems in developing countries have changed profoundly, driven by the proliferation of aquaculture and faltering capture fisheries (Belton and Thilsted, 2014; Tran et al., 2020). The growth of global aquaculture has positively contributed to global food and nutrition security, boosting world fish supplies, mitigating fish output reduction from capture fisheries to meet increasing demand for fish.

The fishery sector in Bangladesh plays an increasingly significant role in the national economy through foreign exchange earnings, animal-source food supply, food security, employment opportunities and supporting overall socio-economic development and sustainable livelihoods (Islam and Shamsuddoha, 2018; Rashid and Zhang, 2019). In 2018, Bangladesh was one of the largest fish producers in the world, third after China and India in the inland capture fishery production, fifth in term of world aquaculture production after China, India, Indonesia and Vietnam (FAO, 2020) and become self-sufficient in fish production (FRSS, 2018). The sector contributed 3.5% of national gross domestic product (GDP), more than one-fourth (25.7%) to the agricultural GDP and 3% of Bangladesh's total foreign exchange earnings in 2017 (FRSS, 2018). In terms of employment, the sector created full-time and part-time jobs for 12% of the Bangladesh population of 165 million people (FRSS, 2018). Fish is one of the most important foods in the Bangladeshi diet, contributing 60% of total animal-source foods while per capita fish consumption in Bangladesh has reached 62.6 g/day (live weight

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equivalent) in 2017 (BBS, 2018).

There are three sources of domestic fish supply in Bangladesh, namely inland culture, inland capture, and marine capture. The total fish production in Bangladesh has increased six-fold and its steadily increasing trend has been maintained over the past 36 years (total output increased from 754,000 metric tons (MT) in 1983–84 to 4,384,000 MT in 2018–19) (FRSS, 2020). The majority of fish supply in Bangladesh comes from inland culture (56.8%) and inland capture (28.2%), the combination of these inland supplies accounted for 85.0% of total production in 2019 (FRSS, 2020). Of which, aquaculture has been playing a crucial role to boost inland fisheries production to meet the increasing fish demand of Bangladesh population (Finegold, 2009). Aquaculture in Bangladesh is practiced in freshwater and brackish water environment with diverse production systems ranging from extensive, improved extensive, semi-intensive to intensive aquaculture. Inland aquaculture in freshwater is mainly comprised of fish farming of Indian major carps Rohu (*Labeo rohito*), Mrigal (*Cirrhinus cirrhosis*), Catla (*Labeo catla*), exotic and other carps (Silver carp (*Hypophthalmichthys molitrix*), Bighead carp (*Hypophthalmichthys nobilis*), Grass carp (*Ctenopharyngodon Idella*), and Common carp (*Cyprinus carpio*), pangasius (*Pangasius*), and tilapia (*Oreochromis niloticus*). Coastal aquaculture mainly includes brackish water shrimp farming in gher culture. Gher culture is the extensive and improved extensive method and means an enclosed area characterized by an encirclement of land along the banks of tidal rivers (Karim, 2006). The contribution of aquaculture in Bangladesh's total fish production has been remarkably increased from 15.5% in 1983–84 to 56.8% in 2018–19 (FRSS, 2020).

Landings from inland capture and marine fisheries in Bangladesh has been increasing at average growth rates of 1.6% and 0.8% over the 1983/1984–2018/2019 period, respectively, contributing 28.2% (1,235,000 MT) and 15.05% (660,000 MT) to total fish production in 2018–19 (FRSS, 2020). Of capture fish species, Hilsa (*Tenualosa Ilisha*), the national fish of Bangladesh accounted for the highest share (12.2%) in the country's total fish production in 2018–19 (FRSS, 2020). Although annual total hilsa catch has sharply declined in 2002–03, its production trends have been gradually reversed, growing at the rate of 3.5% per year from 2005 to 06 to 2014–15 thanks to the government's efforts and donor funded project interventions, including banning on catching brood fish and fries, implementation of jatka conservation program, Hilsa fisheries management action plan (HFMAP) and hilsa spawning protection activities and management of fish sanctuary (FRSS, 2020). The majority of Bangladesh's total catch fish of Hilsa (more than half of total marine catches) originated from the marine capture resources (Miah, 2015).

While fish production and consumption in Bangladesh have been increased in recent years, malnutrition and high levels of micronutrient deficiencies and moderate or severe food insecurity are still significant development challenges. One in every three children under five years in Bangladesh are estimated to be stunted and underweight, one in every five adult women are undernourished, most children under fifteen years live with higher level of nutritional deficiencies and millions of people are suffering micronutrient deficiencies (NIPORT et al., 2016; Fiedler et al., 2014). Inadequate Vitamin A, iron and zinc intake is a major public health problem (Harika et al., 2017).

Fish and other aquatic products are defined as 'irreplaceable' animal-source foods due to their intrinsic nutrient contents, contributing to food and nutrition security in many developing countries (Bogard et al., 2015). In Bangladesh, among animal-source foods, fish is by far the cheapest source and the most important multiple nutrient rich food in the diet. It provides a wide range of micronutrients, protein and fatty acids essential for human brain, bone and nervous system development, growth, cognition and disease prevention (Tacon and Metian, 2013; Nestel et al., 2015; Ezzati and Riboli, 2013). Several fish species from inland capture namely, Chapila, Chela, Darkina, Dhela, Mola, Mola (cultured), Rani, Bou, and Najari Icha, typically consumed whole with head and bones, are rich in essential fatty acids and could contribute more than 25% of the recommended micronutrient intakes including iron, zinc, calcium, iodine, vitamin A and vitamin B12, for pregnant and lactating women and infants (Bogard et al., 2015).

The success and rapid growth of aquaculture in Bangladesh linked to a 'blue revolution' can fulfill the demand of the growing population (Rashid and Zhang, 2019). However, several studies (Bogard et al., 2015; Bogard et al., 2017) highlight that substantial increases in farm-fish consumption have not sufficiently compensated for declines of the nutrient supply from wild fish due to the lower nutritional quality of farmed-fish species compared to non-farmed species. A range of approaches and interventions from both supply and demand side are needed to sustain and enhance capture fisheries and aquaculture contributions to food and nutrition security goals in Bangladesh (Belton et al., 2014). Using a partial economic equilibrium model (AsiaFish), this paper examines future scenarios for fish supply and demand in Bangladesh to 2040 and draws implications on the role of fish in nutrient supply to address the nation's malnutrition, food and nutrition security challenges to meet the national goal of reducing malnutrition and micronutrient deficiencies.

2. Methodology

2.1. Overview of the modelling approach

Multiple modelling approaches have been developed to project supply-demand equilibrium in agriculture and fishery. Some models provide projections at an aggregate level (e.g., global or multi-country scales) where fisheries are incorporated as an agricultural sub-sector. These include the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT model) (Rosegrant and Team, 2012), the AGLINK-COSIMO model (FAO, 2016), the Common Agricultural Policy Regionalized Impact model (CAPRI model), and the Global Biosphere Management Model (GLOBIOM model) (Chang et al., 2018; Latka et al., 2018). Other models provided projections at a higher disaggregation level and focused on fishery sectors at a national scale, e.g., the AsiaFish model developed by Dey et al. (2005 and 2016) and the primal multi-species-multi-sector model proposed by Tran et al. (2017 and 2019). Both groups of modelling approaches have been applied in many studies to analyze the trend and fundamental dynamics of fishery sectors around the world (Rodriguez et al., 2019; Rodriguez et al., 2018; Rodriguez et al., 2011; Henriksson et al., 2017; Chan et al., 2017, 2019; Rosegrant et al., 2017; OECD/FAO, 2017; Phillips et al., 2015; World Bank, 2013; Garcia et al., 2013; Brooks and Philips, 2012; Weeratunge et al., 2010; Delgado et al., 2003).

This paper applied the AsiaFish model (Dey et al., 2005) to the fishery sector of Bangladesh. This modelling approach features partial supply-demand equilibrium for each fish species or group of species. The total demand for fish includes fish consumed by domestic households (consumption), fish used by firms (intermediate inputs), and fish consumed by foreign countries (exports). Fish supply sources include domestic production and imports. The demand for domestic consumption is formalized using the Quadratic Almost Ideal Demand System (QUAIDS) (Edgerton, 1997; Blundell et al., 1993; Banks et al., 1997). The demand function for intermediate inputs and the supply function of domestic producers are derived via the normalized profit function approach (Dey et al., 2005). The formalization of international trade assumes the Armington constant-elasticity-of-substitution (CES) specification (Armington, 1969), differentiating fish species and species groups. The model has seven components (also referred as cores), each contains multiple equations.These components formalize (i) the supply side, i.e., the behaviors of fish producers, (ii) the demand for inputs, e.g., feed, (iii) the consumption side, i.e., the behavior of fish consumers, (iv) the international trade of output, i.e., the import and export of fish, (v) the international trade of input, e.g., the demand for for importef feed, (vi) market equilibrium conditions, and (vii) nutrition indicators. The equations and detailed specifications of the model adapted from Dey et al. (2005) are shown in Annex 2 and a schematic diagram showing relationships among the key blocks of the model was presented in Annex 3.

The nutrition module of the model identified the protein and energy content of fish groups. The model also estimated the macronutrients and micronutrients content of fish species, as motivated Fiedler et al. (2016), who showed evidence for high levels of nutritional deficiencies among children under the age of 15 as well as among non-pregnant and non-lactating women aged 15 to 49 years. Five micronutrients and mineral contents considered in the model were vitamin A, iodine, zinc, iron, and calcium.

2.2. Data and data sources

Calibrating the AsiaFish model requires a comprehensive dataset. This dataset includes disaggregated fish quantity and prices, quantities and prices of inputs for producing fish, and rural and urban population and income. We managed to retrieve some of these data from various sources, including the Department of Fisheries and its publications, FAO (2014), Household Income and Expenditure Survey (HIES), publications of the WorldFish Center, survey data from Agro Solution, and Asian Development Bank (ADB, 2014). Other information is not available, such as the quantity of fish that firms purchase to produce processed fish for human consumption (IDH). To overcome this challenge, we computed IDH as a net residual of domestic production plus import net consumption, export and intermediate inputs.

Table 1 summarizes the data for seven key fish groups in Bangladesh. The seven fish groups were Indian major carp, exotic carp, tilapia, pangasius, shrimps and prawns, hilsa, and other fish. Production of the specified species groups can be produced from four environments (marine capture, inland capture, inland culture, and brackish water culture). The projections of domestic production under the alternative scenarios derived from the model cover the seven fish groups. The table also distinguished rural and urban households. For all species, demands for and supplies are equal. Parameters of the model were drawn from the work by Ahmed et al. (2004).

Table 2 reports the proportion of edible parts to the total body weight of different fish groups. The coefficients for the fish groups represent the median of nutritional coefficients of fish species (e.g., Indian major carp: rohu, mrigal, catla) and fish sizes (e.g., small and regular sized fish for hilsa) reported in Bogard et al. (2016). In this study, the authors inform that, for the nutrient composition analysis, cleaned raw and edible parts of sampled fish from dominant fish sources were washed with deionized water before packing in polyethylene bags and then stored in a deep freezer at —18C. Then, an insulated box, lined with dry ice was used to transport frozen samples to the laboratories in Denmark and New Zealand for analysis. The only exceptions are the vitamin A coefficients for exotic carp and shrimps and prawns obtained from the United States Department of Agriculture (undated) and Belton et al. (2014). Annex A described in detail the nutrition coefficients and proportions of edible parts. An important limitation of the nutrition module is the omission of processed fish. However, the impact of this shortcoming is not likely to be large because processed fish consumption is only about 2% of total fish consumption. Another limitation is that the remaining non-edible parts of the fish, that are highly nutritious parts, are lost from the model. Very little is known about the amount and fate of these “waste” nutrients and how they can be better utilized for human consumption (e.g., in fish-based products).

2.3. Scenario analysis

The model was calibrated to project the dynamics of the fishery sector in Bangladesh until 2040. The year 2010, where comprehensive data were most available for both supply and demand side, was used as the base year. The key drivers, parameter names and values of the model at the baseline level and alternative scenarios are summarized in Annexs 4 and 5.

The business-as-usual (BAU) scenario assumes historical growth rates for exogenous variables, including prices of food items, import prices of fish and fishmeal, export prices of fish, wage rate, fuel prices, prices of non-fish feeds and fish seeds, regional population, and regional incomes. These historical growth rates were estimated from previous studies and several data sources such as ADB (2020 and 2014), BBS (2020, 2018, 2015 and 2013), FAO (2020 and 2014), World Bank (2021) and the United Nations (2014).

A participatory workshop was organized at WorldFish, Penang to

Table 1
Balance sheet for the Bangladesh AsiaFish model, 2010.

Item	Indian major carp	Exotic carp	Tilapia	Pangasius	Shrimps & prawns	Hilsa	Other fish	Total
	Quantity (tons)							
Total Production								
Marine capture	–	–	–	–	56,989	225,325	264,019	546,333
Inland capture	92,009	36,196	252	535	55,132	114,520	755,941	1,054,585
Inland culture	688,770	221,863	104,716	156,375	4059	–	101,706	1,277,489
Brackishwater culture	–	–	–	–	123,280	–	60,000	183,280
Import	–	–	–	–	144	–	7045	7189
Export	19	–	21	–	45,324	8690	38,833	92,887
Rural Consumption	562,381	213,195	79,707	125,487	141,216	186,054	611,278	1,919,318
Urban Consumption	210,327	42,202	24,158	29,805	51,060	141,685	176,600	675,838
Intermediate Demand								
Process	8052	2661	1082	1618	2004	3415	8210	27,043
Fish for fishmeal							353,791	353,791
	Value (million taka) [a]							
Total Production								
Marine capture	–	–	–	–	12,933	55,331	22,398	90,662
Inland capture	11,454	3383	26	52	12,512	28,121	64,130	119,677
Inland culture	85,743	20,738	10,618	15,110	921	–	8628	141,758
Brackishwater culture	–	–	–	–	27,977	–	5090	33,067
Import	–	–	–	–	93	–	562	655
Export	4	–	4	–	28,084	3275	7456	38,821
Rural Consumption	67,014	19,471	7793	11,685	17,446	41,122	64,735	229,265
Urban Consumption	29,177	4401	2738	3321	8634	38,229	23,453	109,953
Intermediate Demand								
Process	1002	249	110	156	272	827	919	3535
Fish for fishmeal	–	–	–	–	–	–	4245	4245

[a] The ADB (2014) indicates an exchange rate of 65.7 taka/US$ in 2010.

Table 2
Nutrition coefficients and edible proportions of fish.

Fish group	Macronutrients		Micronutrients & minerals					Proportion of edible parts [e]
	Energy [a]	Protein [b]	Vitamin A [c]	Iron [d]	Zinc [d]	Iodine [d]	Calcium[d]	
Indian major carp	3630	182	150.0	9.1	10.5	180.0	2100	0.79
Exotic carp	4080	168	90.0	11.0	18.0	255.0	1620	0.81
Tilapia	4010	193	155.0	13.5	13.0	110.0	1075	0.80
Pangasius	6425	173	215.0	17.0	8.8	170.0	338	0.80
Shrimps and prawns	3485	167	540.0	78.5	23.0	730.0	8750	0.40
Hilsa	8190	177	170.0	22.0	15.0	355.0	3600	0.87
Other fish	3840	170	760.0	18.0	17.5	185.0	6880	0.85

Notes: [a] in kilojoules/kg of edible parts ; [b] in grams/kg of edible parts; [c] in micrograms/kg of edible parts; [d] in milligrams/kg of edible parts; [e] 0.79 means that 79% of fish parts are edible.

formalize alternative scenarios. Workshop participants were international and Bangladesh experts, including representatives from public and private sectors, industry associations, research institutions, national and international non-profit organizations in Bangladesh, and academia. The workshop participants have collectively constructed four alternative scenarios (ASs), namely higher productivity of aquaculture (Tilapia, pangasius and rohu carp) (AS1), feed quality improvement (AS2), disease in the aquaculture shrimps/prawns (AS3) and climate change effects (AS4). Experiments with alternative scenarios described below started from 2025 to 2040.

- Scenario 1 (AS1) focuses on the possibility of increasing the productivity of farmed tilapia, pangasius and rohu carp. It assumes a 25% increase in productivity for these species in 2040. In this scenario, the productivity improvement was approximated based on existing or planned government policies and initiatives, e.g., tilapia and rohu production was expected to benefit from the Integrated Agricultural Productivity and National Agricultural Technology projects and the Consultative Group on International Agricultural Research (CGIAR) research program on agri-food fish systems to accelerate innovation, dissemination, and adoption of improved fish strains and best aquaculture management practices by aquaculture farmers in Bangladesh.
- Scenario 2 (AS2) assumes improvements in the quality of feeds where fishmeal output per unit of fish inputs would increase by 25%.
- Scenario 3 (AS3) focuses on the impact of possible disease outbreaks in aquaculture. This scenario assumes that infectious diseases would reduce the output of shrimp and prawn farms by 25% in 2025. However, this negative impact is considered short-term, and the industry would recover to pre-outbreak levels by 2030.
- Scenario 4 (AS4) examines the possible negative impacts of climate change on fishing. Bangladesh is one of the most vulnerable countries to climate change (Mojid, 2020), and many previous studies have concluded that climate change would have significant impacts on the Bangladesh fish sector (e.g., Ahmed and Diana, 2015; Chand et al., 2015; and Bene et al., 2016). Thus, this scenario assumes a productivity decline of 10% and 25% for aquaculture and capture fisheries, respectively.

3. Results

3.1. Business-as-usual (BAU) scenario

Our projection results show that under the BAU scenario, fish supply in Bangladesh is projected to be strong and rise almost to double by 2040 (Table 3). While capture fisheries production is likely to expand at 1.4% per year between 2020 and 2040, aquaculture production is projected to increase from 2583.9 thousand tons in 2020 to 5464.3 thousand tons in 2040 (projected average growth rate at 3.8% per year) (Fig. 1). With sluggish growth of capture fisheries and relatively higher growth of aquaculture, per capita fish consumption at the national level is expected to gradually increase from 25.2 kg in 2020 to about 37.1 kg in 2040, where aquaculture is likely to be the major contributor to the total consumption. The growth in fish demand is mainly driven by the factors,

Table 3
AsiaFish model BAU projected growth of fish production, international trade, per capita consumption, prices and potential nutrients from fish for Bangladesh.

	2010	2020	2030	2040	Growth Rate (2020–2040) %)
Domestic production	000 tons				
Aquaculture	1460.8	2583.9	3646.6	5464.3	3.8
Indian Major carp	688.8	870.8	1137.8	1584.3	3.0
Exotic carp	221.9	429.9	549.4	733.8	2.7
Tilapia	104.7	369.8	659.0	1216.0	6.1
Pangasius	156.4	388.7	616.5	1048.7	5.1
Shrimps & prawns	127.3	125.0	169.6	203.0	2.5
Other Fish	161.7	399.6	514.3	678.6	2.7
Capture fisheries	1600.9	1918.8	2187.4	2545.8	1.4
Indian Major carp	92.0	132.9	152.7	181.0	1.6
Exotic carp	36.2	41.5	43.8	46.6	0.6
Tilapia	0.3	1.7	3.3	6.6	7.0
Pangasius	0.5	13.7	27.7	59.1	7.6
Shrimps & prawns	112.1	115.5	123.6	126.0	0.4
Hilsa	339.8	548.0	601.0	662.3	1.0
Other Fish	1020.0	1065.4	1235.3	1464.0	1.6
Total [a]	3061.7	4502.6	5834.0	8010.1	2.9
International trade [b]	000 tons				
Exports	96.9	75.7	186.8	180.2	4.4
Imports	11.1	63.2	154.0	157.1	4.7
Per capita consumption [b]	kg/person/year				
Rural	16.2	22.7	26.9	35.0	2.2
Urban	23.9	32.6	36.3	40.4	1.1
National	17.7	25.2	29.9	37.1	2.0
Prices	(Taka/kg) (includes processed fish)				
Consumer	129.2	133.5	163.7	208.5	2.3
Producer	125.8	126.7	156.5	191.9	2.1
Potential nutrient supply from fish[c]	(per person per day)				
Micronutrients					
Vitamin A (micrograms)	13.8	17.5	19.5	22.9	1.4
Iron (milligrams)	0.7	0.9	1.1	1.3	1.7
Iodine (milligrams)	8.8	12.1	13.7	16.2	1.5
Zinc (milligrams)	0.6	0.8	0.9	1.1	1.7
Calcium (milligrams)	148.9	185.3	200.3	226.6	1.0
Macronutrients					
Protein (grams)	6.7	9.6	11.3	14.2	2.0
Energy (kilojoules)	173.2	256.5	299.6	371.6	1.9
FMI[d]	353.8	490.4	620.1	774.5	2.3

[a] Sum of the outputs of aquaculture and capture fisheries
[b] Fresh and processed fish.
[c] These estimates exclude nutrients from the consumption of processed (mostly, dried) fish. However, processed fish consumption in Bangladesh in 2010 was only about 2% of total fish consumption.
[d] FMI = Fresh fish used as fishmeal inputs (000 tons).

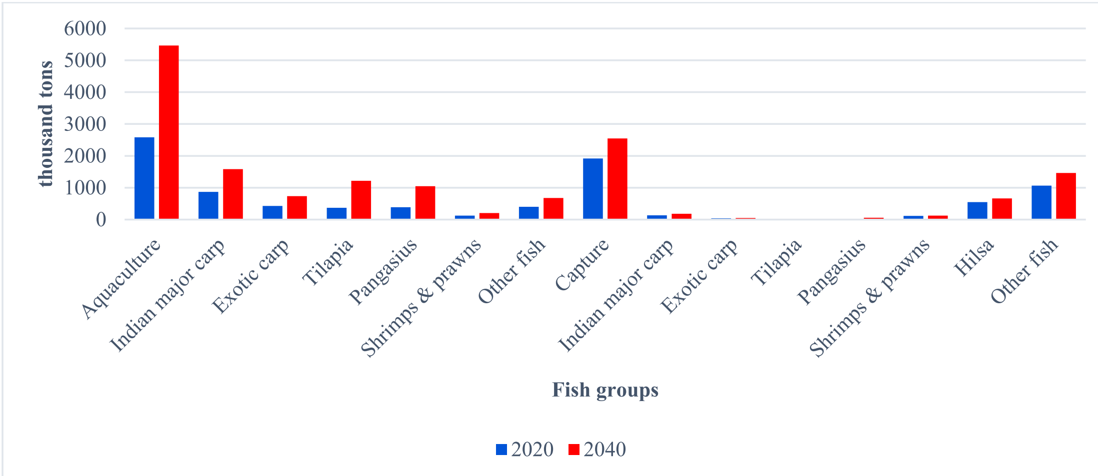

Fig. 1. Projection aquaculture and capture fisheries production in the BAU scenario by fish groups.

namely population growth, evolving consumer preferences, higher income and increased awareness of health benefits of fish consumption. The increase in total fish consumption are mainly attributable to the relatively rapid expansion of per capita fish consumption in rural areas with an average annual growth rate at 2.2% to 35.0 kg and urban areas with at 1.1% to 40.4 kg between 2020 and 2040 (Table 3). The growth rate in per capita fish consumption was twice as large in rural areas relative to urban areas because most rural people stand to benefit from the decline in fish prices and increased fish production associated with rapid commercial aquaculture expansion (Toufique and Belton, 2014). As presented in Table 3, fish exports and imports (fish trade) are expected to increase annually by 4.4% and 4.7%, respectively, over the projection period, with both exports and imports being larger by 2040 (180.2 thousand tons and 157.1 thousand tons, respectively) than in 2020. The major drivers of fish export are rapid growth rate of fish supply and export earnings, while the restaurant trade is the major driver of fish import (Belton et al., 2011). Average producer and consumer prices of fish are projected to increase in 2040 compared to 2020 with likely implications for the poor and vulnerable consumers (Table 3).

As described in Fig. 1, production of all aquaculture species groups is expected to increase between 2020 and 2040. In terms of production share of each fish group, Indian Major Carp (IMC) is expected to remain the largest source of farmed fish supply in Bangladesh followed by Tilapia and Pangasius by 2040. The production of IMC is projected to be almost double in 2040 (1584.3 thousand tons) compared to 2020. Tilapia (from 369.80 thousand tons in 2020 to 1216.0 thousand tons in 2040) and Pangasius (from 388.7 thousand tons in 2020 to 1048.7 thousand tons in 2040) will also likely experience prominent increases in their contribution to overall fish supply in Bangladesh. Similarly, production of the species groups of exotic carp, shrimps and prawns, and other fish species) are projected to increase by between 1.3 and 1.7 times between 2020 and 2040. In terms of potential nutrition contribution from fish, under the BAU scenario, the key nutrient supply from fish including vitamin A, iron, iodine, zinc, calcium, protein and energy in 2040 are projected to increase by between 1.2 and 1.5 times compared to those in 2020 (Table 3). These results reflect the different nutrients contribution from fish as fish is one of the main contributors to the food and nutrition security due to their increasing nutrients supply by 2040.

3.2. Alternative scenarios for growth

Table 4 summarizes the results for the alternative scenarios (ASs) in comparison to the key outcomes associated with the BAU scenario. Apart from demonstrating the potential impacts of interventions or

Table 4
The effects of alternative scenarios on key outcomes (% deviation from the BAU scenario in 2040).

Item	Scenario BAU	Percent deviation from BAU (2040)			
		AS1	AS2	AS3	AS4
Domestic production					
Aquaculture	5464.3	18.2	-0.3	−0.8	−9.4
Indian Major carp	1584.3	21.4	−0.4	0.4	−10.8
Exotic carp	733.7	−18.4	0.9	−3.7	−7.6
Tilapia	1216.0	14.1	0.8	−4.0	−6.1
Pangasius	1048.7	62.3	−0.8	3.8	−15.1
Shrimps & prawns	203.0	−9.1	0.6	−7.5	−7.0
Other Fish	678.6	−2.1	−2.8	−0.1	−6.0
Capture fisheries	2545.7	−0.5	−0.6	0.4	−23.2
Indian Major carp	181.0	−3.8	−0.2	0.0	−25.3
Exotic carp	46.6	−7.9	0.3	−1.7	−23.6
Tilapia	6.6	−19.8	0.4	−2.6	−24.6
Pangasius	59.1	−0.4	−0.6	2.7	−31.0
Shrimps & prawns	126.0	−5.4	0.3	−1.2	−23.5
Hilsa	662.3	2.4	−1.0	1.9	−26.2
Other Fish	1464.0	−0.6	−0.6	−0.1	−21.2
Tota[a]	8010.1	12.3	−0.4	−0.4	−13.8
International trade[b]					
Exports	180.2	7.3	1.6	−0.6	−32.6
Imports	157.1	−7.6	−2.9	−1.4	5.7
Per capita consumption of fish[b]	37.1	13.4	1.6	−0.4	−14.4
Consumer prices	208.5	−5.5	−1.2	−0.1	14.9
Producer prices	191.9	−4.4	−1.1	−0.1	13.1
Potential nutrient supply from fish[c]					
Micronutrients					
Vitamin A	22.9	8.9	4.6	0.0	−18.8
Iron	1.3	11.8	2.4	0.0	−15.7
Iodine	16.2	9.9	1.5	−0.3	−15.9
Zinc	1.1	8.4	1.9	−0.9	−15.9
Calcium	226.6	3.2	4.2	−0.3	−18.8
Macronutrients					
Protein	14.2	14.1	1.6	−0.4	−14.8
Energy	371.6	16.6	1.3	0.3	−16.0
FMI[d]	774.5	−1.2	−19.9	−0.9	0.2

[a] Sum of the outputs of aquaculture and capture fisheries.
[b] Fresh and processed fish.
[c] These estimates exclude nutrients from the consumption of processed (mostly, dried) fish. However, processed fish consumption in Bangladesh in 2010 was only about 2% of total fish consumption.
[d] FMI = Fresh fish used as fishmeal inputs (000 tons).

policies on fisheries sector in Bangladesh, the ASs projections also provide a sense of the sensitivity of fish supply, demand, trade, prices and key nutrients supply from fish to changes in exogenous variables discussed in the method section (e.g., prices of food items, import prices of fish and fishmeal, export prices of fish, wage rate, fuel prices, prices of non-fish feeds and fish seeds, regional population, and regional incomes).

3.2.1. *Increase productivity of farmed tilapia, pangasius and Indian major carp (IMC) (AS1)*

Under the assumption of increase productivity of farmed tilapia, pangasius and rohu carp (AS1), the projection results show that both farmed tilapia, pangasius and IMC outputs would be substantially higher (14.1%, 62.3% and 21.4%, respectively) compared to the BAU scenario by 2040 (Table 4 and Fig. 2). The positive impacts of the productivity improvements are also reflected in the increases in the total aquaculture output (18.2%) and overall fish production (12.3%) but all capture species except hilsa is projected to decline output (0.5%) compared to BAU in 2040 as presented in Fig. 2.

Furthermore, higher productivity tends to cause lower consumer prices of fish, and brings additional benefits to the economy in the form of higher exports, lower imports and increase in per capita fish consumption as shown in Fig. 2. Per capita fish consumption is projected to be 13.4% higher than that in the BAU scenario by 2040. While the fish exports are expected to exceed BAU levels by 7.3% in 2040, fish imports are projected to reduce by 7.6% than BAU levels by 2040. Overall, due to higher fish availability, consumer and producer prices of fish are decline (−5.5% and − 4.4%, respectively) under AS1 compared to BAU. With regards to the potential nutrients contribution from fish presented in Fig. 3, it shows that all nutrients contribution from fish are projected to increase within the range of 3.2% to 16.6% by 2040. The results also suggest significant nutritional benefits particularly increase in both macronutrients (e.g. iron, iodine, Vitamin A and Zinc) and micronutrients (e.g. energy and protein) contribution from fish under this scenario.

3.2.2. *Improvements in the quality of feeds (AS2)*

Scenario 2 (AS2) assumes improvements in the quality of feeds where fishmeal output per unit of fish inputs would increase by 25%. AS2 which simulated through higher quality of feed inputs that yields benefits to the sector. These scenario results presented in Table 4 and Fig. 2 show that total fish production which combines aquaculture and capture fisheries production would be slightly lower, with estimated 2040 production being only −0.4% lower than BAU, but per capita fish consumption would increase by 1.6% as a result of decline in consumer prices. Simulation results also suggest favourable outcomes for exports because fish exports are expected to remain largely unaffected by AS2 relative to BAU. However, fish imports are projected to be 2.9% lower compared to BAU in 2040 due to the slightly increase domestic fish supply of some species and decline in producer prices. The potential nutrition contribution from fish would increase by between 1.3% and 4.6% compared to BAU (Table 4 and Fig. 3). The most attributable nutrients contributions are observed for micronutrients such as Vitamin A (4.6%) and Calcium (4.2%). These projections provide support for earlier assertions on the links between the demand for fish as feed and nutrition.

3.2.3. *Farmed shrimps and prawns' diseases (AS3)*

The scenario of diseases affecting shrimps and prawn's farming (AS3), is projected to have a widespread effect on the production of both the species as well as other aquaculture fish groups. Both shrimps and prawn (−7.5%) fall below BAU projections, with an overall fish production decline of 0.8% from the aquaculture sector (Table 4). As presented in Table 4 and Fig. 2, this also has "knock-on" effects on other key outcomes including decline in exports (−0.6%), imports (−1.4%), per capita fish consumption (−0.4%), prices (−0.1%) and nutrients contribution from fish (between−0.3% and − 0.9%) by 2040 compared to BAU. Most noticeable impacts under this scenario are the declines in aquaculture output and overall fish production. The decline in total fish production tends to reduce per capita fish consumption and fish exports. Lower consumption of fish in turn translates into lower supply of key micronutrients from fish, especially zinc (Table 4 and Fig. 3).

3.2.4. *Climate change impacts (AS4)*

Alternative scenario 4 (AS4) attempts to simulate the effects of climate change on key outcomes which are presented in Table 4 and

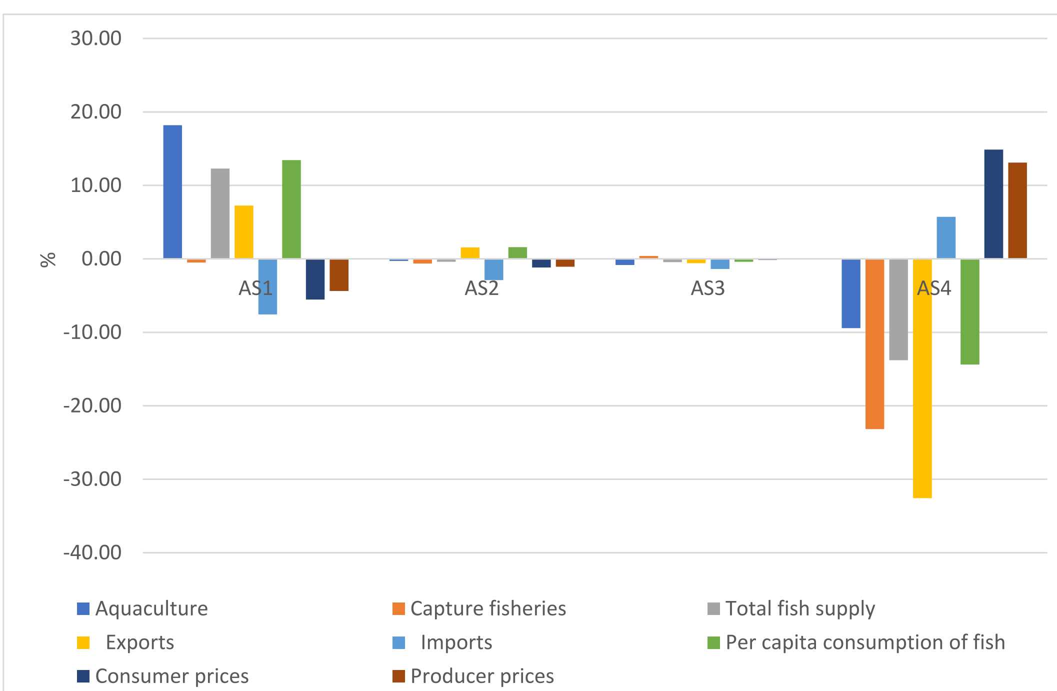

Fig. 2. The percentage deviation from the BAU scenario in 2040 on fish supply, demand, trade and prices.

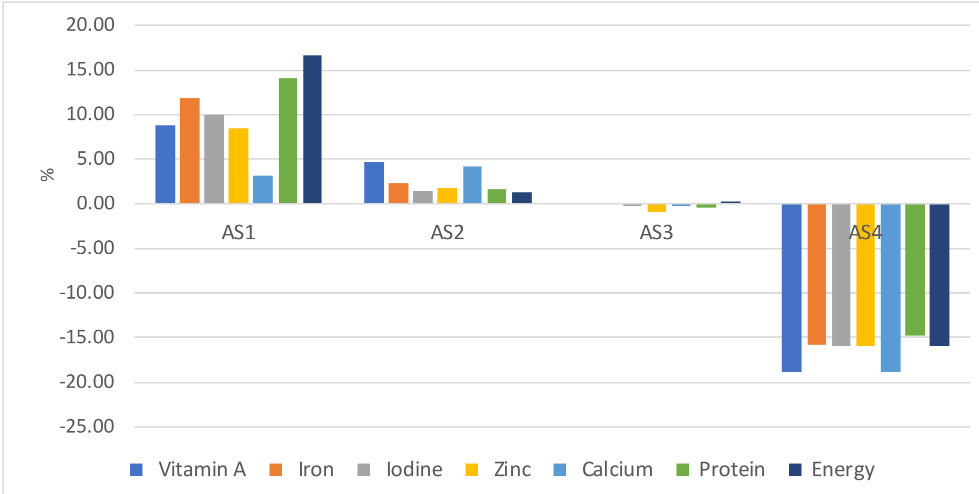

Fig. 3. The percentage deviation from the BAU scenario in 2040 on the nutrient intakes from fish

Fig. 2. It is evident that climate change will negatively affect all fish species production across the aquaculture and capture fisheries. Total fish production including aquaculture and capture fisheries will decline by −13.8% in 2040 relative to BAU but capture fishery production would suffer most (fall within the range of 21.2% to 31%) (Table 4). This lower total production tends to raise consumer prices (14.9% compared to BAU scenario), it is not surprising to observe declines in fish exports and per capita fish consumption by −32.6% and − 14.4%, respectively (Table 4 and Fig. 2). The latter of these impacts causes significant reduction in all types of nutrients contribution from fish within the range of −14.8% and − 18.8% across the nutrient's items under AS4 than BAU scenario (Table 4 and Fig. 3). Most notably, if we compare all the alternative scenarios, this scenario (AS4) will have the worst impacts on different outcomes of fish consumers and producers including fish production, consumption, and prices as well as the role of fish and other aquatic foods in key nutrient supply to contribute to the goal of reducing malnutrition and food and nutrition insecurity.

4. Discussion and policy implications

Fisheries and aquaculture are integral parts of agri-food systems, playing an important role in supplying affordable and more environmentally sustainable fish and other aquatic foods to meet the national objective of ensuring food and nutrition security and also supporting sustainable livelihoods and socio-economic development in Bangladesh and many other developing countries. Early recognition and understanding of critical drivers and challenges influencing the sectors are essential for policy and decision-makers to formulate and guide the sectors' development strategies, policies, plans and interventions to support food and nutrition security and other sustainable development goals. Our results provide some insights into the prospects and challenges of future fish supply, demand, trade, prices and key nutrient sources from fish in Bangladesh under various future scenarios to 2040.

Based on historical trends, the BAU scenario projects the outcome of Bangladesh's fisheries and aquaculture sector development until 2040. In this scenario, fish supply and demand in Bangladesh is projected to grow over time, and the country will remain a net fish exporter by 2040. While the growth of capture fisheries would slow down, as observed in other studies (Tran et al., 2017; (Islam and Shamsuddoha, 2018)), aquaculture development is projected to be strong, and aquaculture will be the major source of future fish supply in Bangladesh to 2040. On the demand side, fish consumption will continue to increase, primarily driven by rapid population growth, higher income, urbanization, diet shift due to increased recognition of health and nutritional benefits of fish consumption. Urbanization leads to increase income that can positively influence the fish consumption of the households because they can afford to pay the higher price of fish with rising incomes. In addition, lifestyle changes due to increased income and dietary shift from plant-source proteins to animal-source proteins due to the increasing knowledge of health benefit of fish consumption can affect fish consumption. The fast-increasing demand from domestic consumers would shrink the net trade surplus, though Bangladesh would remain a (net) fish exporter. Our BAU scenario highlights the importance of accelerating sustainable aquaculture growth and sustaining capture fisheries for contributing to food and nutrition security, one of the most pressing policy priorities in Bangladesh.

Our results of alternative scenario analysis highlight the importance of managing risks in the fishery sector of Bangladesh. As presented in Table 4, AS3 and AS4 show the negative impacts of disease outbreaks and climate change on economic welfare and community health by reducing fish consumption and nutrition supply from fish. In addition to the economic and health conseuquences, this outcome may also cause social impacts when diseases and climate change would reduce the fish supply, pushing up fish price, which would impact low-income people who have limited purchasing power and are most vulnerable to inflation. Therefore, epidemic diseases are considered a type of risk that must be taken into account in aquaculture, the largest fish supply of the country. When Bangladesh is among the most vulnerable countries to climate change; climatic risks may impact both capture fishery and aquaculture and pose a long-term threat of the fishery sector. The outcomes of AS3 and AS4 reveal that managing these risks are essential to a sustainable development of the fishery sector. On the other hand, fisheries operations moderately contribute to greenhouse gas emissions through fossil-fuel-based catching activities, so that, two main approaches - mitigation of the Green House Gases (GHG) and adaptation strategies to cope with changing environment should be considered. Adaptation strategies have the same importance as mitigation actions in countering the climate change. Progress in and technologies and innovations as well as improving fisheries management and governance play an important role in the common goal of mitigation and adaptations (Zhao et al., 2018; Daw et al., 2009). Daw et al. (2009) highlight that adaptation actions may be costly and limited in scope; therefore, GHG reduction remains a priority responsibility for governments, civil society and international organizations.

We also analyze the positive outcomes of public and private investments and interventions to accelerate aquaculture of farmed tilapia, pangasius, and IMC (mainly rohu carp) (AS1) and improvements in feed quality and price (AS2). If successfully realised, these interventions would make fish products more affordable by lowering prices, increasing fish consumption and net export, and decreasing net import.

Our analysis also shows that changes in the fishery sector would directly impact the nutrient supply for Bangladesh people. Climate change would have far-reaching effects on nutrient supply from fisheries products. Since capture fisheries are a significant source of essential micronutrients for many poor and vulnerable consumers, declines in capture fisheries due to the climate change impacts would increase the fish price, jeopardizing the key nutrient contributions from fish to the population of Bangladesh. Thus, it is essential to promote the sustainable management of the capture fisheries and reduce the vulnerability to climate risks via various community-based strategies and adaptations such as integrated coastal zone management, institutional support, technical assistance, provision of high quality information on the risks, changing fishing operations and strong collaboration among the key stakeholders (Ahmed and Diana, 2015; Daw et al., 2009).

Our results highlight the need to support sustainable aquaculture growth to enhance the fishery sector contribution to food and nutrition security in Bangladesh. Pro-aquaculture policies and interventions can be implemented to improve fish farming productivity and promote technological progress to reduce the price of feed – the key aquaculture input, to increase the profitability of fish farmers. In addition, policies should be developed to encourage development and adoption of nutrition-sensitive aquaculture approaches, embracing the diversity of commercially farmed-fish species with nutrient rich small and indigenous species to provide higher nutritional quality and accessibility of fish among the households who are poor and undernourished. As nutrition-sensitive aquaculture (e.g., mola-carp polyculture) can play a crucial role in improving nutrition and health, homestead pond polyculture, a mix of carp with small and indigenous species should be implemented to generate long-term impact on the micronutrient deficiencies to healthy diet.

5. Conclusion

We applied the AsiaFish model to generate fish supply and demand projections and draw insights for fisheries and aquaculture development implications for food and nutrition security in Bangladesh. We find both challenges (e.g., the impacts of climate change and infectious diseases in aquaculture,) and opportunities (fast-growing demand driven by demographic and population growth, possible improvements in productivity and efficiency) for the fishery sector. Our results can be utilized as a preliminary input for policy responses to emerging challenges and opportunities in aquatic food systems in Bangladesh.

Our analysis shows that the aquaculture sector would play an increasingly important role in the fishery sector. It is an important policy priority to support sustainable aquaculture growth to enhance the fishery sector contribution to food and nutrition security. Investments in "nutrition-sensitive" aquaculture approaches can be considered an approach to tackling malnutrition and food insecurity. Furthermore, investments in improving and sustaining the capture fisheries is critical to ensure capture fisheries continue to be a major solution to tackle the malnutrition and food insecurity in Bangladesh. While our analysis is undertaken for the fishery sector of Bangladesh, we contend that its implications may apply to other developing countries facing similar policy challenges and development objectives.

Author contribution statement

Nhuong Tran: Funding acquisition, conceptualization, methodology, data curation and analysis, writing- original writing -review, supervision.

U-Primo Rodriguez: methodology, data curation and analysis, writing -review& editing.

Chin Yee Chan: Funding acquisition, data curation and analysis, writing -review & editing.

Yee Mon Aung: data curation and analysis, writing -review & editing.

Long Chu: writing - review & editing.

Abu Hayat Md.Saiful Islam: writing - review & editing.

Benoy Kumar Barman: writing - review & editing.

Michael John Phillips: Funding acquisition, writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Annex 1 Nutrition data from Bogard et al. (2016) and its classification in the AsiaFish model

Fish group	Nutrient							
Bogard et al. (2016)	AsiaFish model	Vitamin A[a]	Iron[b]	Zinc[b]	Iodine[b]	Energy[c]	Protein[d]	Edible portion[e]
Common Carp	Exotic carp	na	11	22	130	3810	164	na
Grass Carp	Exotic carp	na	5	9	na	3410	152	0.82
Silver Carp	Exotic carp	na	44	14	na	4350	172	0.81
Thai Sharpunti	Exotic carp	120	16	18	380	4660	184	0.80
Ilish	Hilsa	200	19	12	370	10,200	164	0.87
Jatka Ilish	Hilsa	140	25	18	340	6180	190	na
Catla	Indian major carp	220	8	11	180	2670	149	0.79
Mrigal	Indian major carp	150	25	15	150	3630	189	0.77
Rui	Indian major carp	130	10	10	200	4220	182	0.79
Boro Kholisha	Other fish	460	41	23	200	3810	179	na
Maita	Other fish	na	5	7	140	2920	166	na
Koi	Other fish	2950	9	6	na	3540	152	0.86

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Fish group	Nutrient							
Bogard et al. (2016)	AsiaFish model	Vitamin A[a]	Iron[b]	Zinc[b]	Iodine[b]	Energy[c]	Protein[d]	Edible portion[e]
Mola	Other fish	25,030	57	32	170	4000	155	0.82
Mola (cultured)	Other fish	22,260	190	42	330	3850	155	0.82
Baim	Other fish	270	19	11	130	3490	152	0.76
Bele, Bailla	Other fish	180	23	21	250	3840	155	0.54
Chanda	Other fish	3360	21	26	240	3870	147	0.92
Chapila	Other fish	730	76	21	130	3600	179	0.85
Chela	Other fish	1320	8	47	190	3840	205	0.80
Darkina	Other fish	6600	120	40	810	4790	168	0.83
Dhela	Other fish	9180	18	37	95	3940	179	0.90
Ekthute	Other fish	980	15	36	110	4310	172	na
Foli	Other fish	na	17	16	na	5410	157	0.91
Golsha	Other fish	na	18	13	130	2670	119	0.85
Guchi	Other fish	780	27	13	190	7510	171	na
Gutum	Other fish	760	33	25	160	3290	171	0.86
Jat Punti	Other fish	540	22	29	200	7370	155	0.92
Kachki	Other fish	780	28	31	60	3300	169	1.00
Kajuli, Bashpata	Other fish	370	8	12	71	3260	165	0.86
Kakila	Other fish	910	7	19	370	3380	167	0.67
Kuli, Bhut Bailla	Other fish	370	8	20	310	6190	162	na
Magur	Other fish	250	12	7	220	4450	173	0.87
Meni, Bheda	Other fish	600	8	16	130	4120	147	0.71
Modhu Pabda	Other fish	na	5	9	70	6540	149	0.79
Rani, Bou	Other fish	240	25	40	250	3740	191	0.76
Shing	Other fish	320	22	11	na	3060	183	0.78
Taki	Other fish	1390	18	15	180	3870	172	0.87
Tara Baim	Other fish	830	25	12	130	4280	151	1.01
Tengra	Other fish	120	40	31	280	3850	154	0.89
Tit Punti	Other fish	210	34	38	190	2860	171	0.64
Gojar	Other fish	na	4	6	140	3100	187	na
Shol	Other fish	na	4	7	na	3200	172	0.89
Foli Chanda	Other fish	na	3	7	94	3570	176	na
Kata Phasa	Other fish	na	16	31	100	3810	181	0.85
Lal Poa	Other fish	na	17	21	410	4050	205	na
Murbaila	Other fish	na	17	8	190	3100	188	na
Parse	Other fish	na	13	8	69	8130	161	0.84
Tailla	Other fish	na	6	9	260	4250	206	na
Tular Dandi	Other fish	na	21	9	200	3450	193	na
Thai Pangas	Pangas	310	7	7	na	9250	160	0.80
Majhari Thai Pangas	Pangas	120	27	11	170	3600	186	na
Harina Chingri	Shrimps & prawns	na	27	13	260	3330	176	0.40
Najari Icha	Shrimps & prawns	na	130	33	1200	3640	157	na
Tilapia	Tilapia	100	11	12	110	3900	195	0.80
Majhari Tilapia	Tilapia	210	16	14	na	4120	190	na

Notes: [a] in micrograms/kg of edible parts ; [b] in milligrams/kg of edible parts; [c] in kilojoules/kg of edible parts; [d] in grams/kg of edible parts; [e] 0.79 means that 79% of fish parts are edible.

Annex 2. Equations of the model (Adapted from Dey et al., 2005)

Producer core

Effective price of fish and non-feed inputs		
(P1)	$PE_{ik} = \frac{PP_i}{pnum_k} * \frac{\lambda_{ik}}{\lambda num_k}$	$i \in FS \cup AFIDSN$ $k \in K$
Effective price of feed inputs		
(P2)	$PE_{ik} = \frac{PINT_{ik}}{pnum_k} * \frac{\lambda_{ik}}{\lambda num_k}$	$i \in AFIDS$ $k \in K$
Netput quantity per supply unit		
(P3)	$QA_{ik} = \left(\alpha_{ik} + \sum_j \alpha_{ijk} * PE_{jk} + \sum_{l=1} \alpha_{ilk} * v_{ilk}\right) * \lambda_{ik}$	$i, j \in AN$ $k \in K$ $l \in COND_k$
Netput quantity, numeraire per supply unit		
(P4)	$QNUM_k = \left(\alpha_{0k} - \frac{1}{2}\sum_i \sum_j \alpha_{ijk} * PE_{ik} * PE_{jk}\right) * \lambda num_k$	$i, j \in A_k$ $j \in K$
Total netput supply by production category		
(P5)	$QS_{ik} = QA_{ik} * firms_k$	$i \in FS$ $k \in K$
Total supply of fresh fish		
(P6)	$QST_i = \sum_k QS_{ik}$	$i \in FS$ $k \in K$
Total supply of processed fish		

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(P7)	$QST_i = \zeta 1_i \cdot \sum_j QSPROC_{ij}$	$i \in FSN$ $j \in FS$
Fresh fish allocated to the production of processed fish		
(P8)	$QSPROC_{ij} = \sum_k \phi 1_{ijk} \cdot QS_{jk}$	$i \in FSN$ $j \in FS$ $k \in K$

Feed Core

Quantity of fresh fish allocated to the production of fishmeal, by fish type and category		
(I1)	$QSMEALK_{ik} = \phi 2_{ik} \cdot QS_{ik}$	$i \in FS$ $k \in K$
Quantity of fresh fish allocated to the production of fresh feed, by fish type and category		
(I2)	$QSFRESHK_{ik} = \phi 3_{ik} \cdot QS_{ik}$	$i \in FS$ $k \in K$
Quantity of fresh fish allocated to the production of feed for other animals, by fish type		
(I3)	$QSOTHER_i = \sum_k \phi 4_{ik} \cdot QS_{ik}$	$i \in FS$ $k \in K$
Quantity of fresh fish allocated to the production of fishmeal, by fish type		
(I4)	$QSMEAL_i = \sum_k QSMEALK_{ik}$	$i \in FS$ $k \in K$
Quantity of fresh fish allocated to the production of fresh feed, by fish type		
(I5)	$QSFRESH_i = \sum_k QSFRESH_{ik}$	$i \in FS$ $k \in K$
Supply of fishmeal		
(I6)	$QS\_MEAL = \zeta_{fishmeal} \cdot \sum_i QSMEAL_i$	$i \in FS$
Supply of fresh feed		
(I7)	$QS\_FRESH = \zeta_{freshfeed} \cdot \sum_i QSFRESH_i$	$i \in FS$
Re-labeling supply of feeds or $QSFID_i$		
(I8)	$QSFID(\text{"}fishmeal\text{"}) = QS\_MEAL$ $QSFID(\text{"}freshfeed\text{"}) = QS\_FRESH$	$i \in AFIDS$
Demands for fish meal and fresh fish as feed		
(I9)	$QDFID_i = (-1) \cdot \sum_k QA_{ik} \cdot firms_k$	$i \in AFIDSk \in K$

Consumer core

Predicted food expenditure (Stage 1)		
(C1)	$lnFDEX_i = \beta_{0i} + \beta_1{}^* lnPFD_i + \beta_2{}^* lnpfdn_i + \beta_3{}^* lny_i + \beta_4{}^* (lny_i)^2$	$i \in R$
Predicted fish expenditure (Stage 2)		
(C2)	$lnFEX_i = \theta_i + \theta 1_i{}^* lnPF_i + \sum_j \theta 2_{ij}{}^* lnpz_{ij} + \theta 3_i{}^* lnFDEX_i$ $+\theta 4_i{}^* (lnFDEX_i)^2$	$i \in R$ $j \in Z$
Quadratic LA-AIDS share equation (Stage 3), fish types consumed by households		
(C3)	$SH_{ij} = \gamma 0_{ij} + \sum_k \gamma_{ik}{}^* lnPC_{ij} + \gamma 1_i{}^* (lnFEX_j)$ $+\gamma 2_i{}^* (lnFEX_j - STONE_j)^2$	$i, j \in FD$ $j \in R$
Share equation for fish types not consumed by households		
(C4)	$SH_{ij} = 0$	$i \in FDN$ $j \in R$
Stone price index (in logs)		
(C5)	$STONE_i = \sum_j SH_{ij}{}^* lnPC_{ij}$	$i \in FD$ $j \in R$
Aggregate price of fish		
(C6)	$PF_j = \sum_i SHF_i{}^* PC_{ij}$	$i \in FD$ $j \in R$
Share of fish in food expenditure		
(C7)	$SHF_i = \frac{FEX_i}{FDEX_i}$	$i \in R$
Aggregate price of food		
(C8)	$PFD_i = SHF_i{}^* PF_i + (1 - SHF_i)^* PAGFN_i$	$i \in R$
Aggregate price of non-fish food		
(C9)	$PAGFN_{ij} = \sum_j shfn_{ij}{}^* pfn_{ij}$	$i \in R$ $j \in FDFN$
Per capita household demand fish type i in region j		
(C10)		$i \in Fj \in R$

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Share of fish in food expenditure		
(C7)	$SHF_i = \frac{FEX_i}{FDEX_i}$	$i \in R$
	$QD_{ij} = \frac{SH_{ij}{}^{*}FEX_j}{PC_{ij}}$	
Percentage margin on price, import-domestic aggregate		
(C11)	$PC_{ij} = PD_i(1 + mar_{ij})$	$i \in F$ $j \in R$
Total quantity demanded, demand fish type i		
(C12)	$QDT_i = \sum_j QD_{ij} \cdot pop_j$	$i \in Fj \in R$

Trade core of fish

Domestic use of fish		
(T1)	$DOMAB_i = QDT_i + QSFRESH_i + QSMEAL_i + QSOTHER_i + \sum_j QSPROC_{ij}$	$i \in Fj \in FSN$
Composite price of import-domestic aggregate		
(T2)	$PARM_i = \frac{PS_i{}^{*}QHM_i + pm_i{}^{*}QM_i}{DOMAB_i}$	$i \in F$
Domestic demand for domestically produced fish		
(T3)	$QHM_i = \delta 1m^{\sigma m_i{}^{*}}\left(\frac{PARM_i}{PP_i}\right)^{\sigma m_i{}^{*}} DOMAB_i$	$i \in FM$
(T4)	$QHM_i = DOMAB_i$	$i \in FMN$
Conditional demand for imports of fish		
(T5)	$QM_i = \delta 2m^{\sigma m_i{}^{*}}\left(\frac{PARM_i}{pm_i}\right)^{\sigma m_i{}^{*}} DOMAB_i$	$i \in FM$
(T6)	$QM_i = 0$	$i \in FMN$
Composite price of export-domestic aggregate		
(T7)	$PARX_i = \frac{PP_i{}^{*}QHX_i + px_i{}^{*}QX_i}{QST_i}$	$i \in F$
Domestic supply of domestically produced fish		
(T8)	$QHX_i = \delta 1x^{\sigma x_i{}^{*}}\left(\frac{PP_i}{PARX_i}\right)^{\sigma x_i{}^{*}} QST_i$	$i \in FX$
(T9)	$QHX_i = QST_i$	$i \in FXN$
Export supply of fish		
(T10)	$QX_i = \delta 2x^{\sigma x_i{}^{*}}\left(\frac{px_i}{PARX_i}\right)^{\sigma x_i{}^{*}} QST_i$	$i \in FX$
(T11)	$QX_i = 0$	$i \in FXN$

Trade core of feeds

Composite price of import-domestic aggregate of fish feed		
(Z1)	$PARMFID_i = \frac{PP_i{}^{*}QHMFID_i + pmfid_i{}^{*}QMFID_i}{QDFID_i}$	$i \in AFIDS$
Import demand for fish feed		
(Z2)	$QMFID_i = \delta m2fid^{\sigma mfid_i{}^{*}}\left(\frac{PARMFID_i}{pmfid_i}\right)^{\sigma mfid_i{}^{*}} QDFID_i$	$i \in AFIDM$
(Z3)	$QMFID_i = 0$	$i \in AFIDMN$
Domestic demand for domestically produced fish feed		
(Z4)	$QHMFID_i = \delta m1fid^{\sigma mfid_i{}^{*}}\left(\frac{PARMFID_i}{PP_i}\right)^{\sigma mfid_i{}^{*}} QDFID_i$	$i \in AFIDM$
(Z5)	$QHMFID_i = QDFID_i$	$i \in AFIDMN$
Composite price of export-domestic aggregate of fish feed		
(Z6)	$PARXFID_i = \frac{PPFID_i{}^{*}QHXFID_i + pxfid_i{}^{*}QXFID_i}{QSFID_i}$	$i \in AFIDS$
Domestic supply of domestically produced feeds		
(Z7)	$QHX_i = \delta x1fid^{\sigma xfid_i{}^{*}}\left(\frac{PPFID_i}{PARXFID_i}\right)^{\sigma xfid_i{}^{*}} QSFID_i$	$i \in AFIDX$
(Z8)	$QHX_i = QSFID_i$	$i \in AFIDXN$
Export supply of feeds		
(Z9)	$QXFID_i = \delta x2fid^{\sigma xfid_i{}^{*}}\left(\frac{pxfid_i}{PARXFID_i}\right)^{\sigma xfid_i{}^{*}} QSFID_i$	$i \in AFIDX$
(Z10)	$QXFID_i = 0$	$i \in AFIDXN$

Model closure and other equations.

Equilibrium conditions for fish		
(E1)	$QHM_i = QHX_i$	$i \in F$
Equilibrium conditions for fish feed		
(E2)	$QHMFID_i = QHXFID_i$	$i \in AFIDS$
Percentage margin on price, import-domestic aggregate of fish feed		
(E3)	$PINT_{ik} = (1 + marfid_{ik}) \cdot PARMFID_i$	$i \in AFIDS$ $k \in K$
Demand price		
(E4)	$PD_i = PARM_i$	$i \in F$
Supply price		
(E5)	$PS_i = PP_i$	$i \in F$

Nutrition module

Available fish for human consumption per person per day

(N1)	$AFISD_i = \frac{QDT_i + \sum_j QSPROC_{ij}}{365 \cdot \sum_r POP_r}$	$i \in FS$ $j \in FSN$ $r \in R$

Potential nutrition per person per day, by nutrient and fish type.

(N2)	$NPP_{ij} = \eta 1_{ij} \cdot \eta 2_i \cdot AFISD_i$	$i \in FS$ $j \in N$

Potential nutrition per person per day, by nutrient.

(N3)	$TNPP_j = \sum_j NPP_{ij}$	$i \in FS$ $j \in N$

DEFINITIONS

Sets

Set name	Definition	Relations
A_k	Netput vector for category k, $k \in K$	
$AFIDM$	Feeds and fish meal inputs which are imported	$AFIDM \subset AFIDS$
$AFIDMN$	Feeds and fish meal inputs which are not imported	$AFIDMN \subset AFIDS$
$AFIDSN$	Non-feed inputs in production	$AFIDSN \subset AFN$
$AFIDS_k$	Feeds and fish meal inputs in category k, $k \in K$	$AFIDS_k \subset AFN_k$
$AFIDX$	Feeds and fish meal inputs which are exported	$AFIDX \subset AFIDS$
$AFIDXN$	Feeds and fish meal inputs which are not exported	$AFIDXN \subset AFIDS$
AFN_k	Non-fish inputs in category k, $k \in K$	$AFN_k \subset A_k$
$COND_k$	Conditioning variables in category k, $k \in K$	
F	Fish types	
FD	Fish types consumed by humans	$FD \subset F$
FDN	Fish types not consumed by humans	$FDN \subset F$
FM	Fish types which are imported	$FM \subset F$
FMN	Fish types which are not imported	$FM \cup FMN = F$
FS	Fish types produced as fresh fish	$FS \subset F$
FSN	Processed fish types	$FSN \subset F$
FX	Fish types which are exported	$FX \subset F$
FXN	Fish types which are not exported	$FX \cup FXN = F$
K	Production categories	
N	Nutrients	
R	Regions	
Z	Non-fish food types	

Endogenous variables

Variable	Definition	Domain
$AFISHD_i$	Available fresh fish for human consumption, per person per day	$i \in FS$
$DOMAB_i$	Domestic spending on fish types	$i \in F$
$FDEX_i$	Per capita food expenditure by region	$i \in R$
FEX_i	Per capita fish expenditure by region	$i \in R$
NPP_{ij}	Potential nutrition per person, by nutrient and fish type	$i \in FS, j \in N$
$PAGFN_i$	Price index for non-fish food expenditures, by region	$i \in R$
$PARM_i$	Price of the import-domestic aggregate of fish	$i \in F$
$PARMFID_i$	Price of import-domestic aggregate of fish feed	$i \in AFIDS$
$PARX_i$	Price of export-domestic aggregate of fish	$i \in F$
$PARXFID_i$	Price of export-domestic aggregate of fish feed type	$i \in AFIDS$
PC_{ij}	Consumer price by fish type and region	$i \in F, j \in R$
PD_i	Demand price of fish	$i \in F$
PE_{ik}	Normalized effective price of netput element i in category k	$i \in A, k \in K$
PFD_i	Aggregate price of food by region	$i \in R$
PF_i	Aggregate price of fish by region	$i \in R$
$PINT_{ik}$	Price paid for feeds in category k	$i \in AFIDS, k \in K$
PP_i	Producer price of fish or feeds	$i \in FS \cup AFIDS$
PS_i	Supply price of fish	$i \in F$
QA_{ik}	Quantity of netput element i in category k	$i \in AN, k \in K$
$QDFID_i$	Total fresh fish demand by feed type	$i \in AFIDS$
QDT_i	Total household demand by fish type	$i \in F$
QD_{ij}	Household demand by fish type and region	$i \in F, j \in R$
QHM_i	Domestic component of import-domestic aggregate of fish	$i \in F$
$QHMFID_i$	Domestic component of import-domestic aggregate of fish feeds	$i \in AFIDS$
QHX_i	Domestic component of export-domestic aggregate of fish	$i \in F$
$QHXFID_i$	Domestic component of export-domestic aggregate of fish feeds	$i \in AFIDS$
QM_i	Imports by fish type	$i \in F$
$QMFID_i$	Imports by feed type	$i \in AFIDS$
$QNUM_k$	Quantity of numeraire netput in category k	$k \in K$
QS_{ik}	Supply fish type in category k	$i \in F, k \in K$
$QSFID_i$	Quantity supplied of feed types	$i \in AFIDS$
QS_FRESH	Quantity supplied of fresh feed	
$QSFRESH_i$	Quantity of fresh fish type i allocated to the production of fresh feed	$i \in FS$
$QSFRESHK_{ik}$	$QSFRESH_i$ derived from the different sources of fish	$i \in FS, k \in K$
QS_MEAL	Quantity supplied of fish meal	
$QSMEAL_i$	Quantity of fresh fish allocated to the production of fish meal	$i \in FS$
$QSMEALK_{ik}$	$QSMEAL_i$ derived from the different sources of fish i	$i \in FS, k \in K$
$QSOTHER_i$	Quantity of fresh fish allocated to the production of feeds for other animals	$i \in FS$
$QSPROC_{ij}$	Quantity of fresh fish allocated to the production of processed fish (for human consumption)	$i \in FSN, j \in FS$
QST_i	Total supply of a fish type	$i \in F$
QX_i	Exports of a fish type	$i \in FX$
$QXFID_i$	Exports of a fish feed type	$i \in AFIDS$
SHF_i	Average share of fish in food expenditure	$i \in R$
SH_{ij}	Share in fish expenditure, by fish type and region	$i \in F$ $j \in R$
$STONE_i$	Stone price index (in logs) by region	$i \in R$
$TNPPi$	Potential nutrition per person by nutrient	$i \in N$

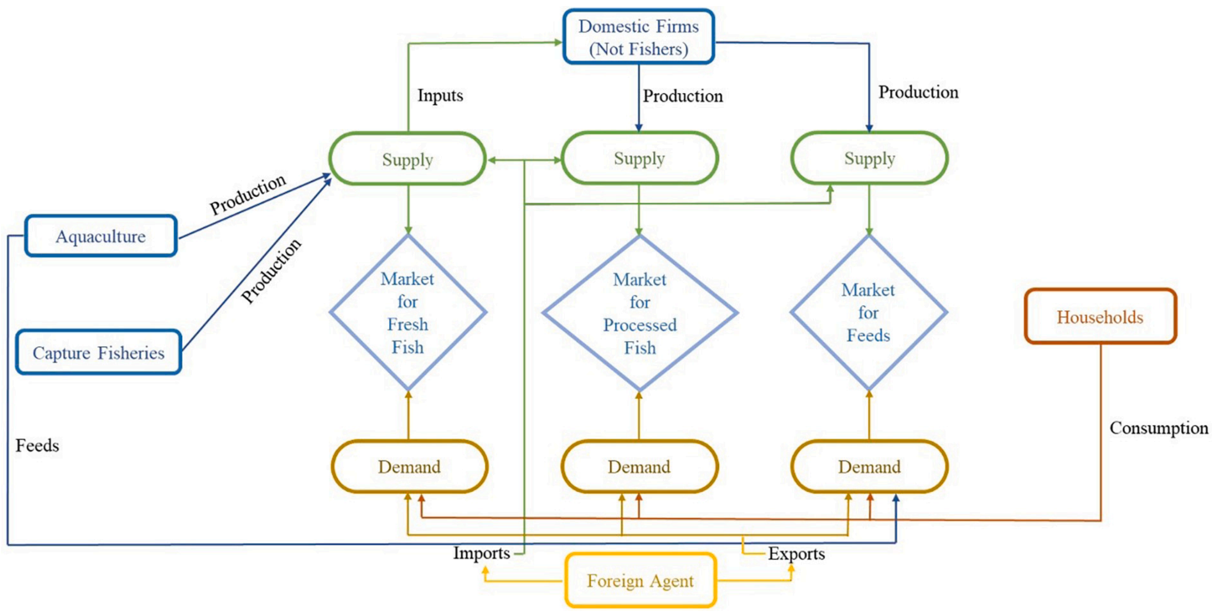
Exogenous variables

Variable	Definition	Domain
λ_{ik}	Technology index of netput i in category k	$i \in A_k, k \in K$
λnum_k	Technology index of the numeraire input in category k	$k \in K$
$firms_k$	Number of supply units category k	$k \in K$
mar_{ij}	Mark-up in the consumer and demand price of a fish type	$i \in F, j \in R$
$pfdn_i$	Aggregate price of nonfood commodities by region	$i \in R$
pm_i	Import price of a fish type	$i \in FM$
$pmfid_i$	Import price of a feed type	$i \in FM$
px_i	Export price of a fish type	$i \in FX$
$pxfid_i$	Export price of a feed type	$i \in AFIDS$
$pfdn_i$	Aggregate price of nonfood commodities by region	$i \in R$
$pnum_k$	Price of numeraire by category	$k \in K$
pop_i	Population by region	$i \in R$
pfn_{ij}	Price of non-fish food items by in region	$i \in FDFN$ $j \in R$
PP_{ik}	Prices of non-fish and non-feed inputs by production category	$i \in AFN_k$ $k \in K$
$shfn_{ij}$	Share of non-fish food items in food expenditure, by region	$i \in Z$ $j \in R$
v_{ik}	Value of conditioning variable i in category k	$i \in F, k \in K$
y_j	Per capita income by region	$j \in R$

Parameters

Parameter	Definition	Domain
α_{ijk}	Supply coefficient of netput element i for netput element j in category k	$i \in A_k$ $k \in K$
a_{ik}	Supply coefficient of conditioning variable i in category k	$i \in FS$ $k \in K$
α_{ik}	Intercept term of netput element i in category k	$i \in FS$ $k \in K$
α_{0k}	Intercept term of the numeraire netput in category k	$k \in K$
$\phi 1_{ijk}$	Proportion of fish type j in category k going into the production of processed fish i	$i \in FSN$ $j \in FS$ $k \in K$
$\phi 2_{ik}$	Proportion of fish type i in category k going into the production of fishmeal	$i \in FS$ $k \in K$
$\phi 3_{ik}$	Proportion of fish type i in category k going into the production of fresh feed	$i \in FS$ $k \in K$
$\phi 4_{ik}$	Production of fish type i in category k going into the production of feeds for other animals	$i \in FS$ $k \in K$
$\zeta 1_i$	Conversion ratio from fresh fish to processed fish type i	$i \in FSN$
ζ_i	Conversion ratio from fresh fish inputs to the output of fish feed i	$i \in AFIDS$
β_{ir}	Stage 1 equation, coefficients for region r	$i = \{1,.0.4\}$ $r \in R$
β_{0i}	Intercept term in stage 1 equation for region i	$i \in R$
θ_i	Intercept term in the stage 2 equation of region i	$i \in R$
$\theta 1_i$	Coefficient of fish price in the stage 2 equation of region i	$i \in R$
$\theta 2_{ij}$	Coefficient of non-fish food price i in the stage 2 equation of region j	$i \in F$ $j \in R$
$\theta 3_i$	Coefficient of expenditure term in the stage 2 equation of region i	$i \in R$
$\theta 4$	Coefficient of the quadratic term in the stage 2 equation of region i	$i \in R$
γ_{ij}	Stage 1 coefficient, of fish type i, for the price of fish type j	$i \in FD$ $j \in R$
$\gamma 0_{ij}$	Intercept term, stage 1 equation for fish type i, in region j	$i \in FD$ $j \in R$
$\gamma 1_{ij}$	Stage 3 coefficient for expenditure term, fish type i and region j	$i \in FD$ $j \in R$
$\gamma 2_{ir}$	Stage 3 coefficient of quadratic term, fish type i and region j	$i \in FD$ $j \in R$
σm_i	Elasticity of substitution, domestically produced and imported versions, fish type i	$i \in FM$
$\sigma mfid_i$	Elasticity of substitution, domestically produced and imported versions, fish feed type i	$i \in AFIDM$
σx_i	Elasticity of transformation, domestically consumed and exported versions, fish type i	$i \in FX$
$\sigma xfid_i$	Elasticity of transformation, domestically consumed and exported versions, fish feed type i	$i \in AFIDX$
$\delta m1_i$	Parameter for domestic production, fish type i	$i \in FM$
$\delta m1\text{fid}_i$	Parameter for domestic production, fish feed type i	$i \in AFIDM$
$\delta m2_i$	Parameter for imports, fish type i	$i \in FM$
$\delta m2\text{fid}_i$	Parameter for imports, fish feed type i	$i \in AFIDM$
$\delta x1_i$	Parameter for domestic use of fish type i	$i \in FX$
$\delta x1\text{fid}_i$	Parameter for domestic use of fish feed type i	$i \in AFIDX$
$\delta x2_i$	Parameter for exports, fish type i	$i \in FX$
$\delta x2\text{fid}_i$	Parameter for exports, fish feed type i	$i \in AFIDX$
$\eta 1_{ij}$	Nutrition coefficients by nutrient i and fish type j	$i \in N$, $i \in FS$
$\eta 1_i$	Proportion of raw fish that is edible, by fish type	$i \in FS$

Annex 3. A schematic diagram of the model



Annex 4. Key drivers at the baseline level and alternative scenarios

Variable name and code	Value	Source	Comment
Price of non-food items	6.44	Sheet BBS, Inflation	CPI growth for non-food items
Import price of fishmeal	14.91	FAO and ADB	FAO (fish) + ADB (exchange rate)
Import price of fish	3.88	FAO and ADB	FAO (fish) + ADB (exchange rate)
Export price of fish	0.65	FAO and ADB	FAO (fish) + ADB (exchange rate)
Wage rate	6.69	BBS, Wage rate	Growth of wages for agri
Fuel prices	6.44	Sheet BBS, Inflation	CPI growth for non-food items
Price of feeds	6.44	Sheet BBS, Inflation	CPI growth for non-food items
Prices of seeds	6.44	Sheet BBS, Inflation	CPI growth for non-food items
Population			
Rural	−0.08	World Bank, World Development Indicators	Growth rate for 2011–2020
Urban	3.41	World Bank, World Development Indicators	Growth rate for 2011–2020
Price of other food items	6.37	Sheet BBS, Inflation	BBS (Food inflation rate so this includes fish)
Real per capita income	5.28	World Bank, World Development Indicators	GDP per capita

Annex 5
Parameter name and value of the model at the baseline and alternative scenarios.

Parameter name	Environment	Fish group	2025: 1st year of shocks		Growth rates (%, average per year, 2025–2040)	
			Baseline	Alternative scenario	Baseline	Alternative scenario
AS1						
LAM	Inland aquaculture	Indian Major Carp	1.27	1.27	1.15	1.90
LAM	Inland aquaculture	Tilapia	3.75	4.68	4.08	5.71
LAM	Inland aquaculture	Pangasius	1.99	2.49	2.50	4.10
AS2						
$\xi_{fishmeal}$	Not applicable	Not applicable	2.5	2	0	0
AS3						
LAM	Brackishwater aquaculture	Shrimps and Prawns	0.88	0.75	−0.14	−0.25
AS4						
LAM	Marine capture	Shrimps & prawns	0.84	0.67	0.07	−1.17
LAM	Marine capture	Hilsa	1.19	0.96	0.21	−1.08
LAM	Marine capture	Other fish	1.36	1.09	2.77	1.50
LAM	Inland capture	Indian major carp	1.32	1.06	0.48	−0.78
LAM	Inland capture	Exotic carp	1.15	0.92	−0.02	−1.27
LAM	Inland capture	Tilapia	5.83	4.67	4.48	3.17
LAM	Inland capture	Pangas	8.79	7.03	3.48	2.19
LAM	Inland capture	Shrimps & prawns	1.08	0.86	−1.42	−2.65

(continued on next page)

Annex 5 (*continued*)

Parameter name	Environment	Fish group	2025: 1st year of shocks		Growth rates (%, average per year, 2025–2040)	
			Baseline	Alternative scenario	Baseline	Alternative scenario
LAM	Inland capture	Hilsa	1.77	1.42	0.18	−1.07
LAM	Inland capture	Other fish	1.02	0.82	0.48	−0.78
LAM	Brackishwater aquaculture	Shrimps & prawns	0.88	0.79	−0.14	−0.80
LAM	Brackishwater aquaculture	Other fish	2.25	2.03	1.35	0.72
LAM	Inland aquaculture	Indian major carp	1.27	1.14	1.15	0.51
LAM	Inland aquaculture	Exotic carp	1.71	1.54	1.03	0.43
LAM	Inland aquaculture	Tilapia	3.75	3.37	4.08	3.44
LAM	Inland aquaculture	Pangas	1.99	1.79	2.50	1.85
LAM	Inland aquaculture	Shrimps & prawns	2.35	2.11	−0.16	−0.79
LAM	Inland aquaculture	Other fish	1.98	1.78	1.36	0.73

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