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Future fish emissions: Insights from modeling foresight scenarios of regional fish supply and demand

November, 2024

WorldFish

CGIAR INITIATIVE ON Low-Emission Food Systems

CGIAR INITIATIVE ON Foresight

Future fish emissions: Insights from modeling foresight scenarios of regional fish supply and demand

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Citation

This publication should be cited as: Chan CY, Tran N and Schindler L. 2024. Future fish emissions: Insights from modeling foresight scenarios of regional fish supply and demand. Penang, Malaysia: WorldFish. Working paper: 2024-61.

Acknowledgments

A special thank you to Yan Hoong and Kai Ching Cheong, who helped us with data analysis. Funding for this study was provided through Mitigate+: Initiative for Low-Emission Food Systems, and the CGIAR Initiative on Foresight. We would like to thank all funders who support this research through their contributions to the CGIAR Trust Fund: www.cgiar.org/funders.

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List of abbreviations

ASEAN	Association of Southeast Asian Nations
BAU	business-as-usual
BSF	black soldier fly
CAPRI	Common Agricultural Policy Regionalised Impact
CH_4	methane
CO_2	carbon dioxide
eq	equivalent
FAO	Food and Agriculture Organization
GDP	gross domestic product
GHG	greenhouse gases
Gt	giga tonnes
IFPRI	International Food Policy Research Institute
IMPACT	International Model for Policy Analysis of Agriculture Commodities and Trade
IPCC	Intergovernmental Panel on Climate Change
LAC	Latin America and the Caribbean
Mt	million tonnes
N_2O	nitrous oxide
PPP	Purchasing power parities
SDG	Sustainable Development Goal
SSA	Sub-Saharan Africa
SSP	Shared Socioeconomic Pathway
UN	United Nations

Executive summary

Highlights

- Aquatic foods provide abundant bioavailable nutrients and are a major protein source for 40% of the world's population. Compared to most terrestrial livestock, fish production has a relatively low carbon footprint, underscoring its significance for achieving sustainable food systems and promoting global food security.
- Under the optimistic *High* scenario in this report, fish supply and per capita fish consumption rise in all regions, with Asia leading in both production and consumption now and in the future. In contrast, the *Risk* scenario projects a future with stagnating fish production and consumption, while the *BAU* follows the direction of historical trends.
- The industrialized parts of Asia display the highest greenhouse gas (GHG) emissions from marine capture fisheries, followed by Sub-Saharan Africa (SSA) and Latin America and the Caribbean (LAC). By 2035, aquaculture emissions will surpass those of capture fisheries, exposing aquaculture production as the main source of GHG emissions among aquatic food production.
- The *High* scenario offers opportunities to tackle malnutrition in South Asia and SSA, with potential benefits for enhancing social and climate justice.
- Low-emission interventions need to focus on feed, waste, and water management in aquaculture to ensure sustainable growth. Such promising systems include coupling crop and fish production to reduce inputs and limit GHG emissions.

The acceleration of climate change poses significant threats to agri-food systems. Global food systems are a major driver of the ongoing climate crisis, as they contribute to GHG emissions, causing global warming and extreme weather events. Approximately one-third of global GHG emissions are attributed to food production processes, representing a major source of emissions for mitigation efforts to target. Aquatic foods are increasingly recognized as a vital part of healthy diets, with a low carbon footprint and minimal human health impacts. However, there is considerable uncertainty around emissions from aquatic foods, particularly from sources such as biogenic methane production from ponds, fuel combustion from motorized boats, and carbon dioxide release from seafloor trawling. To inform policy debates on the future of aquatic foods at the global and regional levels, we employed the International Model for Policy Analysis of Agriculture Commodities and Trade (IMPACT) to explore three scenarios of fish supply and demand: business-as-usual (*BAU*), *Risk*, and *High*.

In this study, our analysis focused on, five global regions—Africa, Asia, Latin America and the Caribbean (LAC), North America, and Oceania—and three subregions— Association of Southeast Asian Nations (ASEAN), SSA, and South Asia. The *High* scenario anticipates that Asia remains the leading global fish producer in 2050, at more than 213.5 million tonnes, while South Asia emerges as the largest producing subregion. Meanwhile, the ASEAN is projected to remain the subregion with the highest per capita fish consumption in all three scenarios. Under the *High* scenario, Africa's fish consumption is expected to approach the current global average by 2050. In contrast, fish consumption and production stagnate under the *Risk* scenario, leading to significant implications for food and nutrition security of vulnerable populations in SSA and South Asia, as population growth outpaces fish production. The *BAU* scenario indicates a continuation of historical trends, limiting the contribution of blue foods to global equality, food security, and scientific innovations. With the most desirable future outlook on climate challenges, the *High* scenario is expected to produce 15% more farmed fish by 2050 than the *BAU* scenario.

A post-model analysis was used to estimate the future GHG emissions associated with aquatic foods across the different regions and subregions under this study. In direct comparison to terrestrial meats, capture fisheries and aquaculture production exhibit relatively low GHG emissions, signifying their distinct role in reducing food system emissions while sustainably fighting malnourishment. Nevertheless, growing production under the *High* scenario in South Asia is projected to result in substantial GHG emissions in the region by 2050. Our results depict aquaculture as the dominant source of emissions by 2035, as those from capture fisheries are expected to plateau. Technological progress and green investments show potential for the sustainable intensification of aquaculture by reducing emissions, increasing output, and adapting to climate impacts. Notable low-emission interventions include implementing co-cultures in aquaponics and optimizing feed and feeding methods, as well as incorporating seaweed farming into aquaculture. Combined rice and fish production in regions with high rates of rice consumption and nutrient deficiencies could benefit human and planetary health by reducing emissions and increasing food production.


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1. Introduction

Food, land, and water systems face unprecedented threats amid the ongoing climate crisis. Current climate action plans for food systems are insufficient to effectively address the increasingly frequent and intense extreme weather events and large interannual climate variabilities (Hendriks et al., 2023; Mbow et al., 2019). In 2022, total GHG emissions, which are mainly composed of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), reached a new record high of 57.4 gigatons (Gt) CO_2 equivalent (eq) (UNEP, 2023). This increase in emissions jeopardizes international climate targets such as those set out in the Paris Agreement, which commits to limiting global warming to 1.5°C and keeping it well below 2°C (UNFCCC, 2015). The latest Intergovernmental Panel on Climate Change (IPCC) Report for the Sixth Assessment confirmed an increase of 1.1°C in global surface temperature between 2011 and 2020 compared to the reference period 1850–1900 (IPCC, 2023). The discrepancy between the de facto GHG emissions and the allowable emissions to reach the 2°C target represents the emissions gap, which under current policies amounts to 16 Gt CO_2eq (UNEP, 2023). Member states further pledged to deliver climate action in the unconditional nationally determined contributions, but even these recorded commitments deviate from the maximum permissible emission by 14 Gt CO_2eq (UNEP, 2023), posing the dual threat of climate catastrophe and food insecurity to the Global South (Hendriks et al., 2023). The urgency for accelerated climate mitigation has never been more critical.

Agricultural production is not only severely affected by climate change, but greatly contributes to the output of harmful GHGs. Global agri-food systems account for approximately 35% of total GHG emissions, with a striking 72% of this output originating from the Global South, accounting for 16.2 Gt CO_2eq in 2021 (Cerutti et al., 2023; Crippa et al., 2021; FAOSTAT, 2024). These systems hold the potential to contribute 16%–25% of climate solutions between 2030 and 2050 under the two climate forcing scenarios known as Representative Concentration Pathways at 8.5 and 4.5, respectively (IPCC, 2022; Riahi et al., 2017). Agri-food emissions are divided into farm-gate emissions, which arise during production, land-use change and supply chain emissions. At 39%, production accounts for the largest share of total GHG emissions from agriculture, followed by 32% emitted by land use and land use change, and 29% from post-production activities (Crippa et al., 2021). Given that food systems are a major contributor to global GHG emissions, there is an urgent need for a comprehensive transformation of diets and food systems to achieve the United Nations (UN) Sustainable Development Goals (SDGs) and the targets of the Paris Agreement (Rockström et al., 2020).

The production of animal protein is estimated to account for around half of all GHG emissions associated with food production over the past two decades (Herrero et al., 2016; Webb & Buratini, 2016). In contrast, aquatic foods produce protein with lower emissions per unit of output compared to nearly all land-based sources of animal protein (Tsakiridis et al., 2020; Turrell, 2019). GHG emissions from aquatic foods represent around 10%–11% of agri-food emissions, with aquaculture contributing 7% (Hall et al., 2011) and captures fisheries accounting for 4% (Barange et al., 2018; Parker et al., 2018). These emissions encompass pre-farm, on-farm and post-farm or post-dock processes, as well as emissions from land-use change and fuel combustion from fishing boats and larger fishing fleets (Parker et al., 2018). The steady increase in global annual per capita fish consumption, doubling from 10.8 kg in 1970 to 20.6 kg in 2021, translates to increased marine and inland fishing efforts from 63 million tonnes (Mt) to 91 Mt (FAO, 2023c), subsequently leading to an increase in emissions from fuel combustion during these 50 years (Greer et al., 2019). Industrial and small-scale fisheries together increased their fuel combustion emissions from 47 Mt CO_2eq to 207 Mt CO_2eq (Greer et al., 2019).

The necessity of large-scale mitigation across all sectors is critical to limit climate change impacts, including the severe consequences for marine biomass production, fishery landings and ecosystem health. A loss of 10% of all exploitable marine biomass is anticipated under high-emission scenarios (Blanchard & Novaglio, 2024). In regions heavily reliant on fish for food and nutrition security, the losses in maximum catch potential are expected to reach between 30% and 50% (Bindoff et al., 2019; Blanchard & Novaglio, 2024; Lam et al., 2016). Additionally, the poleward migration of commercially targeted species, driven by ocean warming, is expected to disproportionally affect tropical and subtropical marine areas (Bindoff et al., 2019; Duarte et al., 2020). Conversely, the risk of biomass loss is significantly reduced under low-emission scenarios (Blanchard & Novaglio, 2024).

Following the recommendations of the EAT-Lancet commission (Willett et al., 2019), aquatic foods are increasingly recognized as a critical part of a healthy diet with comparably little impact on the environment and a minimal contribution to global emissions (Chan, Prager, et al., 2021; FAO, 2024c; Poore & Nemecek, 2018; Willett et al., 2019). Aquatic foods, or "blue foods," serve as an essential source of nutrients (Golden et al., 2021), providing 17% of crude animal protein globally and containing a number of readily available micronutrients, such as iron, zinc, selenium, calcium, and iodine (Boyd et al., 2022; FAO, 2024c). Over 40% of the world's population obtains more than 20% of its protein supply from aquatic foods (FAO, 2024c). Meanwhile, dietary transitions and growing population fuel the global demand for aquatic foods (Naylor et al., 2021). Recent studies suggest that many fish species are significantly less GHG intensive than terrestrial meats (FAO, 2024c; Gephart et al., 2021; Springmann et al., 2018), positioning aquatic foods as a favorable option for reducing the environmental footprint of agri-food systems.

Nevertheless, large uncertainties exist around the amount of emissions from aquatic foods in the future. Addressing these uncertainties is crucial to assess the environmental impacts of aquatic foods and optimizing their role in food system transformation. To bridge this research gap and inform policy debates on the future of aquatic foods, we developed three scenarios of future production: business-as-usual (*BAU*), *High*, and *Risk*. We first project future fish supply and demand at the global, regional, and subregional levels to 2050 using IMPACT. Second, we conduct post-model analysis to extrapolate future GHG emissions from both capture fisheries and aquaculture for the *BAU* scenario, analyzing future emission trends at all three levels.


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2. Material and methods

2.1. Fish foresight modeling

In recent decades, aquatic foods have become more integrated into foresight models of the agriculture and land-use sectors. Several partial-equilibrium economic models started integrating fish commodities, such as the IMPACT fish model (Chan et al., 2021; Chan et al., 2019; Kobayashi et al., 2015; World Bank, 2013b), the AgLINK-COSIMO model (Lem et al., 2014; OECD/FAO, 2021), the Global Biosphere Management Model, and the Common Agricultural Policy Regionalised Impact (CAPRI) model (Chang et al., 2018; Deppermann et al., 2019; Heckelei et al., 2018; Latka et al., 2018). These economic models focus on analyzing the future supply and demand of fish by simulating the impacts of external drivers such as technological progress, population growth, income growth, and climate change on fish production, consumption, and trade at the global, national, and regional levels. Some studies using the CAPRI model focus on simulating the economic impact of fisheries policies on aquafeed production and different fish commodities. Overall, these comprehensive models focus on medium- or long-term projections at the global and regional levels. Other partial equilibrium modeling approaches, such as the AsiaFish model (Dey et al., 2016; Tran et al., 2023; Tran et al., 2017) and the multi-species–multi-sector equilibrium model (Tran et al., 2019; Tran et al., 2022), developed by WorldFish, provide more disaggregated projections of the fish sector at the country level. Stakeholder consultation inputs, coupled with historical data, are used to generate projections aligned with historical trends and simultaneously provide direction for future projections.

Delgado et al. (2003) were pioneers in using the IMPACT fish model to project global fish production, consumption, and trade for the 1997–2020 period, as published in *Fish to 2020* by the International Food Policy Research Institute (IFPRI) and WorldFish (Delgado et al., 2003). A decade later, the follow-up study, *Fish to 2030*, was commissioned by the World Bank in collaboration with the IMPACT modeling team at the IFPRI, the Fisheries and Aquaculture Department of the Food and Agriculture Organization (FAO), and the University of Arkansas at Pine Bluff (World Bank, 2013a). This report incorporates lessons learned from the previous report and a newly developed fish module of the IMPACT model for the 2000–2030 period (World Bank, 2013a).

Whereas *Fish to 2020* focused on the consumer perspective, using fish species aggregation based on market characteristics, the new model incorporated development in the aquaculture sector and the global seafood markets based on production systems, feeding regimens, and fish diets. The data was disaggregated to envision the link between the fish and agricultural markets and to reflect on the rising role of aquaculture production. Linkages exist through feed markets, which supply the livestock and aquaculture sectors with fishmeal and fish oil ingredients, which are used in both productions. Similarly, both sectors compete for plant-based feeds from terrestrial agriculture, as these feeds play a major role in livestock and aquaculture production. In the IMPACT model, the increasing importance of the linkages between the fish and livestock production, along with the rapid rise in aquaculture compared to capture fisheries, require a market analysis of demand for seafood. In 2017, WorldFish and the IFPRI published *Fish to 2050* in the ASEAN region (Chan et al., 2017), which included substantial model updates to simulate FAO's latest historical trends and to adjust future projections in the ASEAN region up to 2050. It takes industry-specific socio-economic and bio-physical factors into account, such as fisheries management regimens, ecosystem carrying capacity, and fish production targets defined by national governments. Previous reports (Chan et al., 2017; Kobayashi et al., 2015; World Bank, 2013) presented detailed descriptions of the model structure and model updates. From 2019 to 2021, further updates and calibrations were conducted for Africa (Chan et al., 2019), alongside a post-model analysis to extrapolate future employment and investment costs in the African fish sector (Chan, Tran, et al., 2021) This effort involved extensive consultations with experts during multiple stakeholder consultation workshops to enhance the collaborative effort and improve our future projections.

In this study, our analysis focused on the global level, encompassing the five regions (Africa, Asia, the LAC, North America, Oceania) and three subregions (ASEAN, SSA, South Asia). Since these regions are heterogeneous and dynamic, they exhibit profound socio-economic disparities (Table 1). North America and Oceania are the wealthiest regions, with the highest gross domestic product (GDP), while regions such as South Asia and the ASEAN showed notable GDP growth between 2012 and 2022 (World Bank, 2023). Regions with the lowest GDP per capita also have large shares of malnourishment, illustrating the correlation between poverty and hunger (World Bank, 2023). In contrast, high-income regions display the largest animal protein consumption and generally higher per capita fish consumption (FAO, 2023a). Regarding demographic development, Oceania, SSA, and South Asia have the highest population growth rates, while the population in North America and the LAC region almost stagnates. Regions with lower population growth tend to have high urbanization rates (World Bank, 2023). Among all of the regions, Asia stands out for its dominant role in global fish production, representing the largest share of both capture fisheries and aquaculture production (FAO, 2023a; World Bank, 2023).

2.2. Scenarios

Building upon the previous IMPACT fish model, the current model replicates observed trends in fish supply and demand at both the global and regional levels. The model is updated using historical production, consumption, and trade data compiled by FAO up to the most recent year available (FAO, 2023a, 2023b). In this study, we update additional historical production data until 2021. Furthermore, it incorporates the latest historical population and GDP data as part of its model updates (FAO, 2023a, 2023b; World Bank, 2022). Three scenarios are examined in this study: the *BAU* scenario and the two alternative scenarios, *High* and *Risk*. These scenarios are derived from the Shared Socioeconomic Pathways (SSPs) 1, 2, and 3, which represent distinct climate scenarios paired with socio-economic outlooks (Riahi et al., 2017). Notably, the alternative scenarios do not analyze capture fisheries production. These two scenarios diverge from *BAU* projections starting from 2026 and extending through 2050. The future projection results are presented in two phases: the initial phase covers projections from the latest year of historical data up to 2035, while the subsequent phase extends from 2036 to 2050.

BAU

The *BAU* scenario, also known as SSP 2, represents a middle-of-the-road trajectory that aligns with historical trends, reflecting moderate economic growth that varies across the regions and subregions in this study. A gradual decrease in the population growth rate, indicates a slower pace of demographic expansion over time. Moreover, this scenario presents moderate challenges in adapting to and mitigating climate change while successively degrading the environment (Riahi et al., 2017).

As listed in Table 2, future projections anticipate a notable decline in annual GDP growth rates across all of the regions under the *BAU* scenario from 2021 to 2050, compared to historical growth from 2000 to 2021. Except Africa and SSA, all of the regions experience slower growth in the second half of the projection period (2036–2050) compared to the first (2021–2035). The annual GDP growth rate of Africa and SSA accounts for 4.7% and 5.2% from 2036 to 2050, respectively, which is roughly 0.02% to 0.2% higher than the rate from 2021 to 2035, indicating higher economic development in the latter period for Africa. Overall, Africa is projected to add US$11.0 trillion in GDP from 2021 to 2050. Within Asia, projections show that the ASEAN's GDP will reach US$5.4 trillion by 2050, while South Asia is expected to reach USD$15.8 trillion. Overall, the global GDP growth rate is declining under the *BAU* scenario from 5.1% per annum to 2.1% by the end of the second projection period, increasing from US$33.2 trillion in 2000 to US$156.8 trillion in 2050.

Under the *BAU* scenario, global population is expected to reach 9.5 billion in 2050, with a growth rate of 0.8% annually until 2035 and a reduced rate of 0.5% until the middle of the century. Based on historical evidence, Africa's population growth will exceed those of other global regions, as it is projected to add 1.1 billion people by 2050. Furthermore, Oceania is projected to experience the second-highest population growth, reaching a population of 60 million within the same time frame. In contrast, other global regions such as the ASEAN, Asia, LAC, and North America are expected to undergo moderate annual population growth between 0.6% and 0.8% until 2035, and almost halved growth rates for the second phase of the projections (2036–2050).

Indicators	Year	Global	Africa	SSA	Asia	ASEAN	South Asia	LAC	North America	Oceania
Demographic and socio-economic status[a]										
Population (million)	**2022**	**7,950.9**	1,424.8	1,211.2	4,687.2	679.4	1,919.3	659.3	372.3	44.8
Population growth (%)	**2012–2022**	**1.1**	2.5	2.7	0.9	1.0	1.2	0.9	0.7	1.6
Urban population (%)	**2022**	**56.9**	44.5	42.4	52.0	51.2	35.8	81.6	82.9	67.0
GDP (current US$ trillion)	**2022**	**101.3**	2.9	2.1	37.2	3.6	4.4	6.8	27.6	2.0
GDP per capita (current thousand US$)	**2022**	**12.7**	2.1	1.7	7.9	5.3	2.3	10.3	74.1	44.7
GDP growth (%)	**2012–2022**	**3.0**	1.9	1.8	3.9	3.8	6.6	0.9	4.3	1.2
Undernourishment (%)	**2021**	**9.2**	19.2	21.6	9.4	5.2	16.3	6.8	2.5	7.7
Unemployment (% total labor force)	**2022**	**5.8**	7.1	6.7	5.5	2.6	7.0	7.0	3.8	3.6
	Year	**2019**		2019			2021	2021		
Population below US$ 2.15 a day (2017 purchasing power parities (PPP) (%)		**9.0**	n.a.	35.4	n.a.	n.a.	10.9	4.6	n.a.	n.a.
Contribution of fish to food supply[b]										
Total fish production (Mt)	**2022**	**185.4**	12.0	8.1	129.5	32.2	22.9	17.1	5.6	1.8
Capture production (Mt)	**2022**	**91.0**	9.7	7.3	46.6	17.9	9.2	12.8	5.0	1.6
Aquaculture production (Mt)	**2022**	**94.4**	2.3	0.7	82.9	14.3	13.8	4.3	0.6	0.2
Share of aquaculture production (%)	**2022**	**50.9**	19.3	9.0	64.0	44.5	60.0	25.2	11.5	13.0
Aquaculture average annual growth (%)	**2012–2022**	**4.0**	4.4	4.7	4.0	4.1	7.9	6.1	0.6	2.4
Contribution of fish to food and nutritional status[c,d]										
Fish consumption (Mt)	**2019**[c]	**157.3**	13.1	9.2	111.9	26.3.	17.8	6.7	8.3	1.0
Fish consumption (kg/capita/year)	**2019**[c]	**20.3**	9.9	8.5.	24.2	39.6	9.1	10.3	22.3	23.1
Fish protein (g/capita/year)	**2022**[d]	**5.5**	2.6	n.a.	6.8	n.a.	2.9	n.a.	4.8	5.6
Animal protein (g/capita/day)	**2022**[d]	**38.1**	15.5	n.a.	34.3	n.a.	19.9	n.a.	81.9	62.2
Fish/animal protein (%)	**2022**[d]	**14.5**	16.6	n.a.	19.8	n.a.	14.4	n.a.	5.8	9.0

Author's computation from data sources: [a](World Bank, 2023), [b](FAO, 2024b), [c](FAO, 2023b), [d](FAO, 2024a)

Table 1. Demographic and socio-economic status, and contribution of aquatic foods to food security in different regions and the world.

High

The *High* scenario, derived from SSP 1, represents an optimistic sustainable development scenario. Compared to the *BAU*, this scenario anticipates higher economic growth rates and slower population growth (Riahi et al., 2017). Population growth declines significantly in various regions, while Asia, the ASEAN, and LAC even experience negative rates. Moreover, this scenario emphasizes significant investment in research and development, using sustainable technological advancements to alleviate inequality, reduce energy intensity, and increase land productivity. These advancements enhance society's ability to address and adapt to climate change.

Similar to the *BAU* scenario, Africa and SSA are projected to have higher economic growth in the second half of the projection, accounting for US$23.6 trillion and US$20.7 trillion in 2050, respectively. Within the *High* scenario, the global GDP is projected to reach US$189.4 trillion by 2050, which is 20.8% higher than the *BAU* scenario.

Furthermore, the *High* scenario anticipates a slower annual population growth than the *BAU* across all of the regions, except for North America. Notably, the ASEAN, Asia, and LAC experience negative population growth between 2036 and 2050, resulting in declining population sizes. Altogether, the *High* scenario is expected to reduce the historical population growth rate of 1.2% to 0.2% and to deviate from the *BAU* scenario by 60% over the same period of time.

Risk

In contrast to the *BAU* and *High* scenarios, the *Risk* scenario (derived from SSP 3) represents the slowest GDP growth rates across all of the regions, indicating a future with slow economic development. Rapid population growth in the developing regions contrasts drastically with slow growth in the developed regions, signifying rising inequalities and regional resource scarcity over time. Notably, unequal distribution persists when it comes to investments in education and healthcare, especially in low-income countries. This scenario also projects prolonged challenges to global and regional cooperation because of nationalist movements, security threats, regional conflicts, and a global health crisis (Riahi et al., 2017). Minimal improvements in living standards and limited investment in international coordinating organizations lead to sparse cooperation between high- and low- or middle-income countries on climate change and other issues. This reflects a future with high climate change adaptation and mitigation challenges, resulting in an increase in vulnerabilities to climate-related shocks (O'Neill et al., 2017).

The *Risk* scenario is characterized by slower GDP growth rates, which are expected to be 0.4%–1.8% lower across some of the regions by 2050 compared to the *BAU* scenario. Africa and SSA experience the largest negative growth compared to the *BAU* scenario, projecting a GDP of US$10.3 trillion and US$8.3 trillion, respectively, by 2050.

In the *Risk* scenario, the assumption of ongoing inequalities causing the population growth rate is projected to be higher in the developing regions and lower in the developed regions. Africa (comprising of SSA), Asia (including the ASEAN and South Asia), and LAC experience annual population growth between 0.8% and 2.2% in the first phase of projection and then 0.5% to 1.9% in the second, which is 0.1% to 0.3% higher than the *BAU* scenario. On the other hand, North America and Oceania experience a slower population growth under this scenario, accounting for approximately 0.3%–0.4% annually in the first phase of projection and 0.4% to 0.5% in the second. Table 2 summarizes GDP and population growth under the *BAU, High* and *Risk* scenarios from 2000 to 2050 across the various regions.

2.3. Post-model estimation of future GHG emissions

The fish emission factor is a coefficient that describes the rate at which a given fishing or fish farming activity releases GHG into the atmosphere. Yet, due to the informal and dispersed nature of the fish sector, quality emissions data are limited for both capture fisheries and aquaculture at the regional level. We extrapolated the total GHG emissions across different commodities using the fish emission factor/intensity and production databases from various secondary sources, including FAO (2022a, 2023a, 2023b); MacLeod et al. (2020); Parker et al. (2018); Poore and Nemecek (2018); Porter et al. (2016); and Tran et al. (2023). To account for inconsistent data, we further scrutinize the compiled dataset to ensure a synchronized assessment.

Growth rate (%)	Global	Africa	SSA	Asia	ASEAN	South Asia	LAC	North America	Oceania
					GDP growth rate (%)				
Historical[a]									
2000–2021	**5.1**	6.9	7.6	6.7	8.4	8.9	3.9	4.1	6.6
BAU									
2021–2035	**2.8**	4.7	5.0	3.5	2.8	5.0	2.9	1.8	2.4
2036–2050	**2.1**	4.7	5.2	2.1	2.0	3.8	2.3	1.2	2.1
High									
2021–2035	**3.5**	6.2	6.9	4.4	3.4	6.0	3.6	2.2	2.8
2036–2050	**2.7**	6.4	7.0	2.6	2.5	4.6	2.9	1.6	2.5
Risk									
2021–2035	**2.2**	3.7	3.9	2.8	2.3	4.0	2.4	1.4	1.7
2036–2050	**1.1**	3.0	3.3	1.1	1.3	2.3	1.4	0.6	0.9
					Population growth rate (%)				
Historical[b]									
2000–2019	**1.2**	2.6	2.8	1.1	1.2	1.5	1.1	0.9	1.7
BAU									
2019–2035	**0.8**	1.9	2.1	0.6	0.7	1.0	0.7	0.8	1.3
2036–2050	**0.5**	1.3	1.4	0.2	0.2	0.6	0.3	0.5	0.9
High									
2019–2035	**0.7**	1.7	1.8	0.5	0.5	0.8	0.5	0.8	1.3
2036–2050	**0.2**	0.9	1.0	-0.03	-0.02	0.3	-0.02	0.6	0.8
Risk									
2019–2035	**1.0**	2.2	2.4	0.8	0.8	1.3	1.0	0.4	1.0
2036–2050	**0.8**	1.8	1.9	0.6	0.5	1.1	0.7	-0.1	0.5

Sources: Historical data retrieved from [a]World Bank (2022); [b]United Nations (2022)

Table 2. Historical (2000–2021) and future (2021–2035, 2036–2050) population and GDP growth across the study regions.

3. Results

3.1. Future fish supply and demand under the *BAU*, *Risk* and *High* scenarios

Fish production under the *BAU* scenario

Using the IMPACT model, we conduct the future *BAU* projection to 2050 using the SSP 2 scenario across the different regions under the study. The historical trend implies that global fish supply grew 1.8% annually from 2000 to 2021, increasing from 126.0 Mt in 2000 to 182.1 Mt in 2021 (Table 3). Under the *BAU* scenario, global fish production is expected to increase by 23.6% (42.9 Mt) from 2021 to 2035 and is likely to increase another 14.8% from 2036 to 2050. This indicates that global fish production will continue to rise until the middle of the 21st century, although at slower rates than in the past.

Total fish production (Mt)	Global	Africa	SSA	Asia	ASEAN	South Asia	LAC	North America	Oceania
2021[a]	**182.1**	12.7	8.0	126.9	31.4	21.7	17.7	5.9	1.7
2035	**225.0**	13.0	8.4	163.5	41.7	32.5	19.4	6.5	1.3
2050	**258.4**	13.7	8.6	191.9	44.8	44.3	22.1	6.9	1.4

Data source: [a]FAO (2023c)

Table 3. Fish production under the *BAU* scenario.

Global aquaculture produced 90.9 Mt of fish in 2021, representing half of total fish production. Under the *BAU* scenario, aquaculture production is expected to grow further and reach 131.9 Mt in 2035 and then 165.2 Mt in 2050 (Figure 2). This represents an increase of 81.7% relative to 2021 and an additional 74.3 Mt in absolute terms by 2050 (Table 4). However, while the total quantity continues to increase, the average annual growth rate of aquaculture production is projected to slow down over the coming 25 years, from 5.0% in the 2000–2021 period to 2.7% in 2022–2035 and then 1.5% in 2036–2050.

Total aquaculture production (Mt)	Global	Africa	SSA	Asia	ASEAN	South Asia	LAC	North America	Oceania
2021[a]	**90.9**	2.3	0.7	80.3	13.8	12.8	3.8	0.6	0.2
2035	**131.9**	3.0	0.8	116.4	22.8	23.5	6.4	1.0	0.4
2050	**165.2**	3.6	0.9	144.9	25.9	35.2	9.2	1.4	0.6

Data source: [a]FAO (2023c)

Table 4. Aquaculture production under the *BAU* scenario.

Asia remains the major aquaculture producer in the world, representing 88.3% of total production as of 2021. Nevertheless, aquaculture growth across the continent is expected to decelerate, with an annual increase of 2.7% from 2021 to 2035 and 1.5% from 2036 to 2050. By 2050, aquaculture production in Asia is expected to reach 144.9 Mt. Within the continent, the ASEAN region and South Asia are projected to contribute significantly, representing 17.9% and 24.3% of total production in Asia by 2050. Specifically, aquacultural production in the ASEAN and South Asia would reach 22.8 Mt and 23.5 Mt by 2035, and then 25.9 Mt and 35.2 Mt by 2050, respectively. In contrast, regions such as LAC, North America, and Oceania are expected to show moderate growth in aquaculture production, at 2.2%–3.9% through 2050.

Between 2000 and 2021, Africa's growth in aquaculture production was relatively high, at an annual rate of 8.7%. Despite the slow growth rate of 1.9% and 1.2% for the first and second projection phases, Africa is expected to produce 3.6 Mt of fish under the *BAU* scenario by 2050. SSA is poised to become a significant player in aquaculture, with a few countries leading, and the region is expected to contribute 25% of the total aquacultural output in Africa by 2050. Despite the historically high growth rate of 13.0% from 2000 to 2021, this rate is projected to drop to 1.0% between 2021 and 2050 under the *BAU* scenario because of low outputs.

Fish production under the ***Risk*** and ***High*** scenarios

Under the pessimistic *Risk* scenario, the total global fish supply is projected to increase from 182.1 Mt in 2021 to 225.0 Mt in 2035 (Figure 1), with an average annual growth rate of 1.5%. From 2036 to 2050, growth is expected to continue, albeit at a slower pace of 0.5% annually. From 2021 to 2050, the overall increase in global fish supply in this scenario is anticipated to add 54.1 Mt, representing a 29.2% reduction from the *BAU* scenario. This difference amounts to approximately 22.2 Mt fewer in absolute terms compared to the *BAU* scenario, attributed to constrained environmental considerations and slow technological progress.

In contrast to the *BAU* and *Risk* scenarios, the *High* scenario projects strong global growth rates in total fish production from 2021 to 2035, at approximately 1.8% annually, driven by sustainable development, technological advancements, and environmental conservation. This growth trajectory is sustained from 2036 to 2050 at around 1.3% annually, highlighting a continued emphasis on sustainable practices and effective resource management. By 2050, global fish supply is projected to reach 282.9 Mt, which is 9.5% higher than the *BAU* scenario and the highest level among all three scenarios.

In the *Risk* scenario, driven by higher population growth in the developing regions and slower economic development, the share of aquaculture production is anticipated to decrease slightly, with an estimated 125.6 Mt by 2035 and 143.0 Mt by 2050. Under this scenario, total aquaculture production would be 13.2% lower than in the *BAU* scenario by 2050. Conversely, under the *High* scenario, aquaculture production is projected to slightly increase to reach 140.6 Mt by 2035. With greater technological advancement and fewer mitigation challenges, the global aquaculture supply is projected to reach 189.8 Mt by 2050, surpassing the *BAU* scenario by 15%.

Regardless of the scenarios, Asia continues to dominate the aquaculture sector, accounting for approximately 88% of total aquaculture production in 2050 (Figure 2). In the *Risk* scenario, the annual growth rate of aquaculture production declines from 2.7% in the *BAU* scenario to 2.2% in the first phase of the projection, reaching 110.7 Mt in 2035. Subsequently, production is expected to grow at a slower rate in the second phase, amounting to 125.0 Mt in 2050, with an average annual growth rate of 0.8% compared to the *BAU* annual rate of 1.5%. In contrast, the *High* scenario anticipates the highest aquaculture production, exceeding both the *BAU* and *Risk* scenarios, adding 13.2 Mt more than the *Risk* scenario in 2035 and 21.6 Mt more by 2050.

The ASEAN and South Asia remain the main producing regions in the *BAU*, reaching 22.8 Mt and 23.5 Mt of aquacultural production in 2035, respectively. Until 2050, these regions are expected to generate 25.9 Mt to 35.2 Mt under the *BAU* scenario. The *High* scenario further boosts estimated production by 9.4%–10.8% in 2035 compared to the *BAU*, increasing to 23.6% and 26.1% in 2050. In contrast, the *Risk* scenario projects a reduction of 6.8%–7.9% in aquaculture production for both the ASEAN and South Asia in 2035, and a further decline of 19.1%–22.4% relative to the *BAU* scenario by 2050.

Africa and the SSA region have historically been the fastest growing aquacultural producers, boasting average annual growth rates of 8.7% and 13.0%, respectively. However, all three scenarios indicate a slower growth trajectory for aquaculture compared to these historical rates. Under the *High* scenario, Africa is estimated to experience growth of 42.7% from 2021 to 2035, reaching 3.5 Mt by the end of the first projection phase. Aquaculture production for Africa is then projected to slow down its production slightly, increasing 31.4% from 2036 to 2050 and reaching 4.6 Mt in 2050. Projections for the *Risk* scenario indicate an aquaculture output that is 10.6% lower than that of the *BAU* scenario by 2050. SSA alone is projected to reach 1.4 Mt of aquaculture output by 2050 under the *High* scenario, marking a 49.8% increase over the *BAU* projection. Conversely, the *Risk* scenario anticipates a 9.0% decrease in SSA compared to the *BAU* projections.

LAC has historically been among the faster-growing aquaculture-producing regions. Under the *Risk* scenario, the projected additional production in the region is estimated to be 19.7% lower than the *BAU* from 2021 to 2050. Conversely, the *High* scenario projects a 17.6% increase compared to the *BAU*. North America is expected to reach 1.2 Mt of aquaculture production under the *Risk* scenario, but a 33% higher output of 1.6 Mt under the *High* scenario.

Figures 1 and 2 depict the projections of total fish supply under the *BAU*, *Risk*, and *High* scenarios at the regional level. By 2050, the total regional fish supply is estimated to be 1.0%–17.8% lower in the *Risk* scenario than the *BAU*. In contrast, fish supply is projected to be 3.4%–20.8% higher in the *High* scenario compared to the *BAU*.

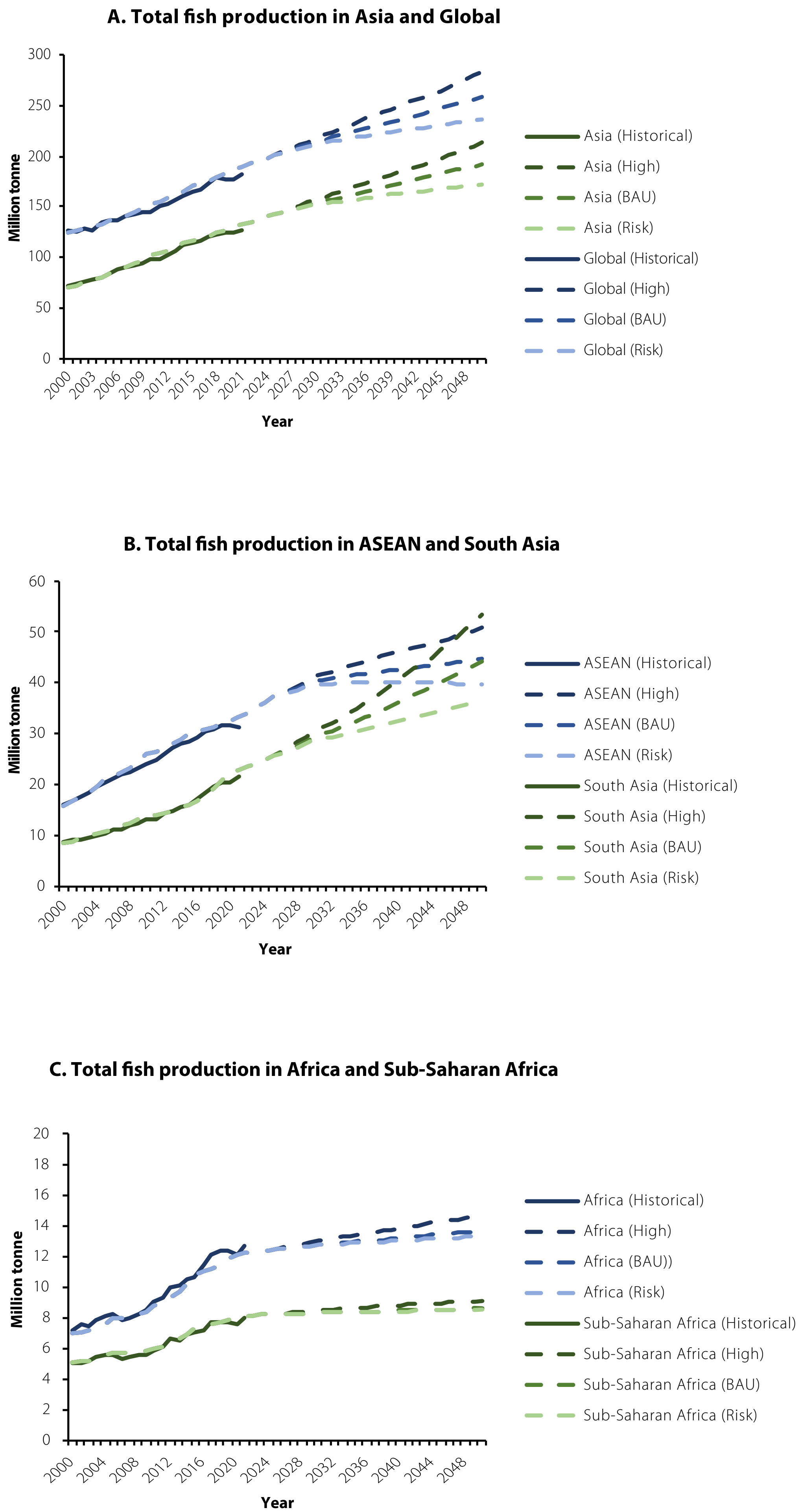


Figure 1. Total fish production under the BAU, High, and Risk scenarios for (A) Asia and Global, (B) ASEAN and South Asia, and (C) Africa and Sub-Saharan Africa.

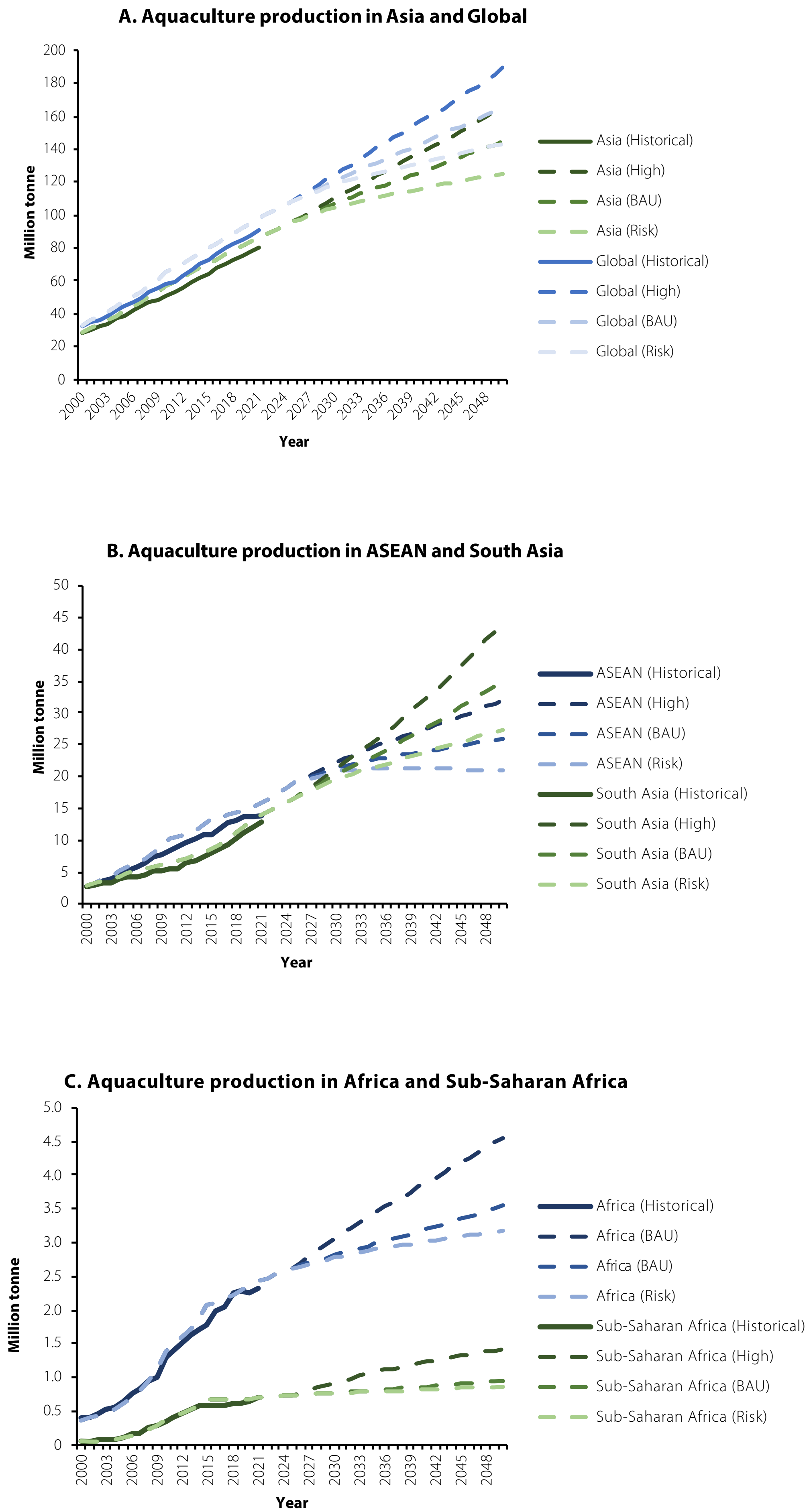


Figure 2. Total aquaculture production under the *BAU*, *High*, and *Risk* scenarios for (A) Asia and Global, (B) ASEAN and South Asia, and (C) Africa and Sub-Saharan Africa.

Fish consumption under the *BAU* scenario

Globally, the *BAU* projections indicate that per capita fish consumption is expected to remain nearly stagnant, increasing only slightly from 20.3 kg in 2019 to 21.3 kg in 2035, and further to 23.2 kg by 2050, marking a 14% rise from 2019 levels (Table 5).

In LAC, Oceania, and SSA, per capita fish consumption is projected to decline during the initial projection phase, followed by an upward trend thereafter in the second. In SSA, domestic fish supply is expected to fall 4.9 Mt short of demand by 2035, leading to a slight reduction of per capita fish consumption from 2019 to 2035.

Despite the initial decline in SSA and Oceania, almost all of the regions are projected to consume more fish per capita by 2050, except for LAC, where levels in 2050 are expected to be lower than in 2019. Notwithstanding the decrease in per capita fish consumption in SSA during the first phase of projection, Africa is projected to have a rise in per capita fish consumption as a whole, with an increase of 62% from 10.0 kg in 2019 to 16.2 kg by 2050. To reach the current global average of 20.3 kg, Africa will require an additional 30.1 Mt of fish supply to meet domestic demand by 2050.

Asia, including the ASEAN and South Asia subregions, is expected to experience a steady increase in per capita fish consumption, from 24.2 kg in 2019 to 26.5 kg in 2035 and then to 28.3 kg in 2050. This is driven by factors such as urbanization, growing income levels, the expansion of fish markets, and increased awareness of the role of fish in healthy diets (OECD/FAO, 2021). By 2050, the *BAU* scenario demonstrates a surplus of fish production in South Asia because of lower fish consumption per capita, which is as low as in Africa (about half the global average) but is expected to rise. Meanwhile, the population in South Asia is expected to surge from 1.9 billion in 2019 to 2.3 billion people in 2035, reaching 2.5 billion in 2050. To attain global fish consumption of 20.3 kg, South Asia requires 7.1 Mt of fish supply to meet this demand by 2050.

Annual per capita fish consumption (kg)	Global	Africa	SSA	Asia	ASEAN	South Asia	LAC	North America	Oceania
2019[a]	20.3	10.0	8.7	24.2	39.6	9.1	10.3	22.3	23.1
2035									
High	22.7	13.5	9.9	28.3	56.9	12.1	9.6	26.9	22.1
BAU	21.3	11.9	8.6	26.5	50.9	11.0	9.3	25.7	21.3
Risk	20.1	10.4	7.5	25.2	47.0	10.0	8.9	26.1	20.9
2050									
High	27.2	21.4	16.1	32.9	80.8	16.8	10.8	34.3	28.3
BAU	23.2	16.2	11.8	28.3	63.3	13.6	9.8	30.0	25.1
Risk	19.7	11.2	8.1	24.3	50.4	10.6	8.7	30.7	23.1

Data source: [a]FAO (2023b)

Table 5. Annual per capita fish consumption in 2019 and projections for 2035 and 2050 under the *BAU*, *High* and *Risk* scenarios.

Fish consumption under the *Risk* and *High* scenarios

Under the *Risk* scenario, global fish consumption is projected to rise from 157.3 Mt in 2019 to 199.3 Mt by 2050. However, per capita fish consumption is expected to fall from 20.3 kg in 2019 to 19.7 kg by 2050 (Table 5). This decline, despite rising total consumption, is attributed to higher population growth, which results in a 15% lower per capita figure compared to the *BAU* scenario, where consumption would rise to 23.2 kg in 2050. This indicates that high population growth is outpacing fish consumption, and each consumer will be eating less fish in the future, potentially leading to food and nutrient deficiencies in vulnerable rural communities. In contrast to the *BAU* and *Risk* scenarios, global per capita fish consumption under the *High* scenario increases from 20.3 kg in 2019 to 22.7 kg in 2035, further increasing to 27.2 kg in 2050.

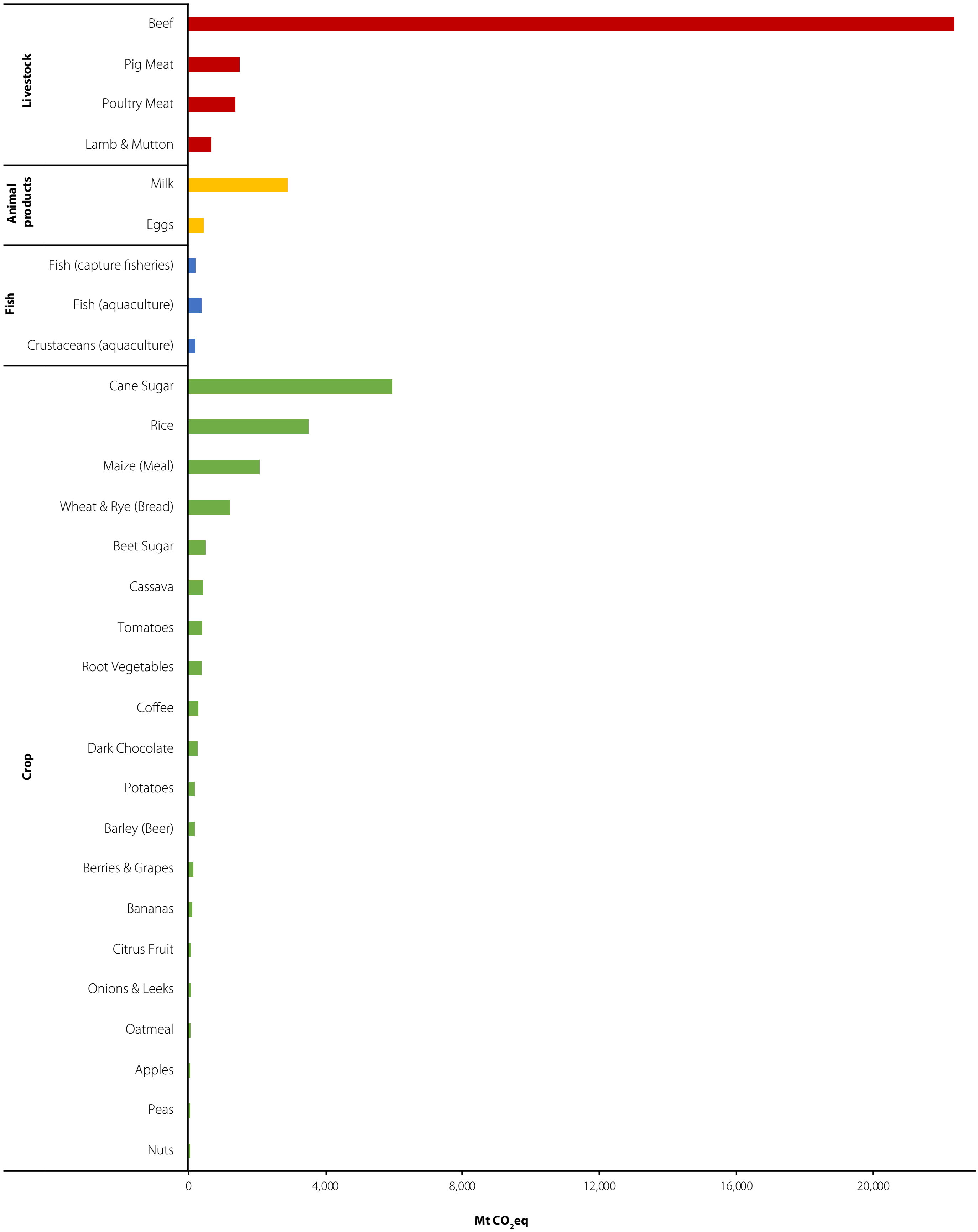
LAC and SSA are projected to experience declines in per capita fish consumption under the *Risk* scenario. In LAC, the average is likely to drop from 10.3 kg in 2019 to 8.9 kg in 2035 and then to 8.7 kg by 2050. Compared to the *BAU* scenario, per capita fish consumption in this region declines 4.3% in 2035 and drops to 11.2% by 2050. In SSA, the average is projected to decrease from 8.7 kg to 7.5 kg in 2035 under the *Risk* scenario, and then increase slightly to 8.1 kg in 2050, which still results in a decrease of 31.4% compared to the *BAU* scenario by 2050.

In the *High* scenario, all of the regions exhibit moderate growth rates in annual per capita fish consumption during the initial projection phase from 2019 to 2035, ranging from 0.5% to 2.8%. Subsequently, this growth accelerates slightly from 0.8% to 3.1% annually from 2036 to 2050. Notably, the ASEAN, Africa, and SSA experience considerable increases in fish consumption compared to the *BAU* scenario. By 2035, per capita consumption in these regions is projected to grow between 11.8% and 15.1% over the *BAU* scenario. By 2050, growth is more pronounced, as much as 27.6%–36.4% higher than in the *BAU* scenario. The outstanding fish consumption in the ASEAN region is projected to be 60.3% higher under the *High* scenario compared to the *Risk* scenario and 27.6% higher than the *BAU* in 2050.

3.2. GHG emissions of fish

3.2.1. Comparison of global GHG emissions for fish and other commodities

A comparison between the total GHG emissions of livestock and fish reveals significant discrepancies in their environmental impacts, despite both being staple foods in human diets. Figure 3 distinctly displays the extraordinary amount of total emissions from the global food system that beef production accounts for, at 22,362.6 Mt CO_2eq, which is the highest share of total emissions among the listed commodities. Following beef, other livestock products such as pig and poultry meat also exhibit substantial emissions, reaching 1,481.8 Mt CO_2eq and 1,361.9 Mt CO_2eq, respectively. Similarly, other animal products such as eggs and milk are associated with GHG emissions exceeding 400 Mt CO_2eq and 2,000 Mt CO_2eq, respectively. In contrast, fish, whether sourced from capture fisheries or aquaculture, present significantly lower emissions. The capture fisheries sector reports emissions of 200.62 Mt CO_2eq, while fish from aquaculture, despite being the highest in the fish category, only emit 376.0 Mt CO_2eq. This highlights that even the most carbon-intensive form of fish production remains well below emissions from terrestrial meat production. Within the crop category, highly produced commodities like wheat and rye for bread, maize for meal, and rice remarkably contribute to emissions, surpassing 1,000 Mt CO_2eq, exemplifying their substantial environmental footprint. Crop products such as nuts, peas, and fruits (like apples and citrus) have moderate emissions, collectively falling below 100 Mt CO_2eq. Overall, Figure 3 illustrates this contrast, emphasizing the need for sustainable practices in food production to reduce GHG emissions.



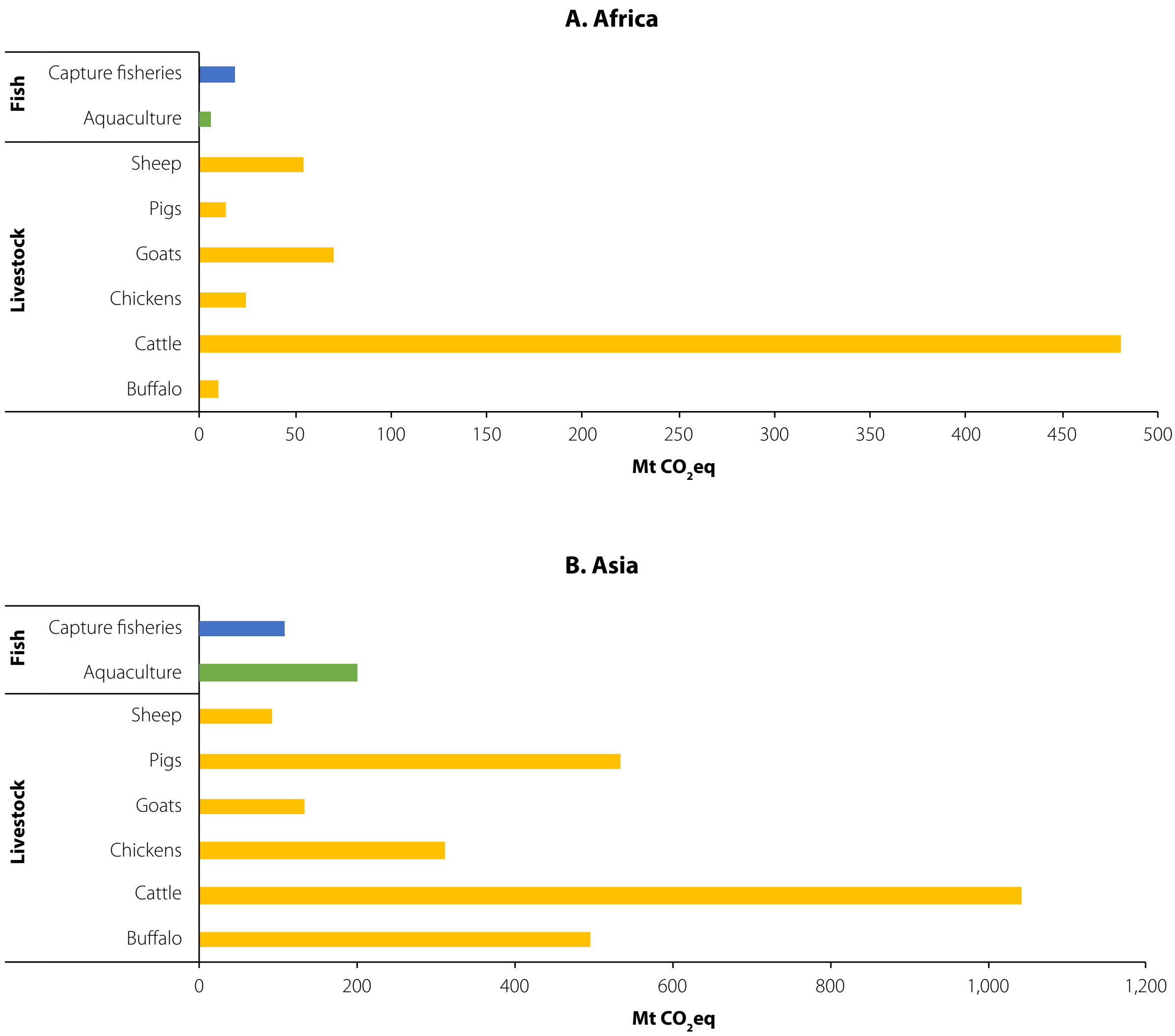
Source: Author computation of emissions from data in Poore and Nemecek (2018)

Figure 3. Total GHG emissions across different commodities in 2021.

3.2.2. Comparison of total GHG emissions from fish and other commodities in Africa and Asia

Historical data from FAO (2022a) highlights the significant GHG emissions in 2015 from livestock in Asia and Africa, particularly cattle and buffalo, which far exceeded emissions from aquaculture and capture fisheries. In Asia, cattle and pigs contributed notably high emissions, reaching 1,043.6 Mt CO_2eq from cattle and 535.2 Mt CO_2eq from pigs. These values are significantly higher than emissions from either aquaculture (199.5 Mt CO_2eq) or capture fisheries (108.7 Mt CO_2eq) within the region. Correspondingly, African ruminant production represents substantial emissions, with cattle alone contributing 480.8 Mt CO_2eq and goats 70.6 Mt CO_2eq. Pig emissions are significantly lower in Africa, mainly because of considerably lower production in Africa. The 10.6 Mt of pigs produced in Asia accounts for 40 times more GHG emissions than African production.

Similarly, GHG emissions from Asian poultry production are considerably higher, with chickens contributing 312.4 Mt CO_2eq in Asia and 24.1 Mt CO_2eq in Africa. African aquaculture and capture fisheries exhibit lower GHG emissions compared to livestock production of sheep, goats, chicken, and cattle, while capture fisheries account for 18.5 Mt CO_2eq and aquaculture just 5.5 Mt CO_2eq. Although emissions from Africa's capture fisheries outweigh those from aquaculture by 13.0 Mt CO_2eq, the situation is reversed in Asia. Because of the continent's highly developed aquaculture sector, emissions in Asia exceed those of capture fisheries by 90.8 Mt CO_2eq. In aggregate, fish production in Asia exhibits significantly higher total emissions, considering the large fish surplus compared to Africa. Nevertheless, beef production emissions outweigh all forms of fish production on both continents.

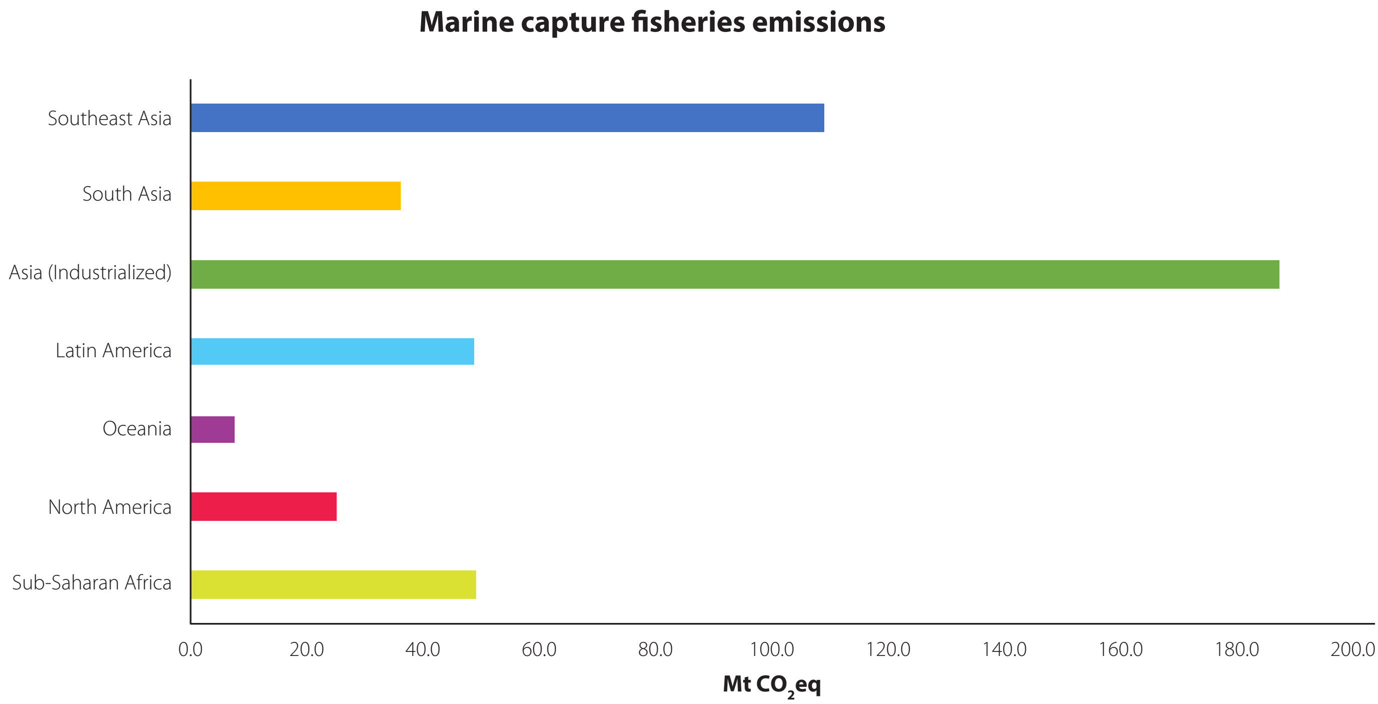


Source: Author's computation from data in FAO (2022a, 2023a, 2023c)

Figure 4. Total GHG emissions from fish and livestock in Africa (A) and Asia (B) in 2015.

3.2.3. Comparison of total GHG emissions from marine production at the regional level

We use data from FAO (2023c) and Porter et al. (2016) to compare total GHG emissions in 2021 from marine capture fisheries production across the different regions (Figure 5). Asia emerges as the region with the highest such emissions, having contributed 187.1 Mt CO_2eq. Within Asia, Southeast Asia alone accounts for a substantial portion, having emitted approximately 109.2 Mt CO_2eq. Significantly lower carbon footprints are attributed to emissions from marine capture fisheries production in SSA, LAC, and South Asia, at 49.0, 48.9 and 36.1 Mt CO_2eq, respectively. North America accounts for 24.9 Mt CO_2eq and Oceania 7.5 Mt CO_2eq, demonstrating the least GHG-intensive marine fisheries.

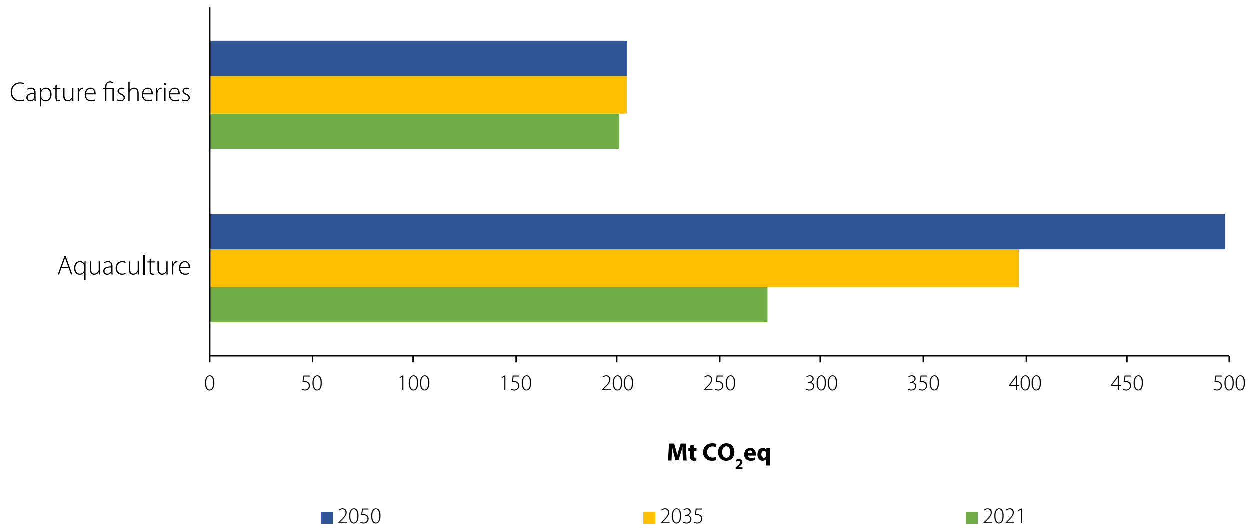


Source: Author's computation from data in FAO (2023c); Porter et al. (2016)

Figure 5. GHG emissions from marine capture fisheries in 2021 across the study regions.

3.2.4. Future GHG emissions of fish under the *BAU* scenario

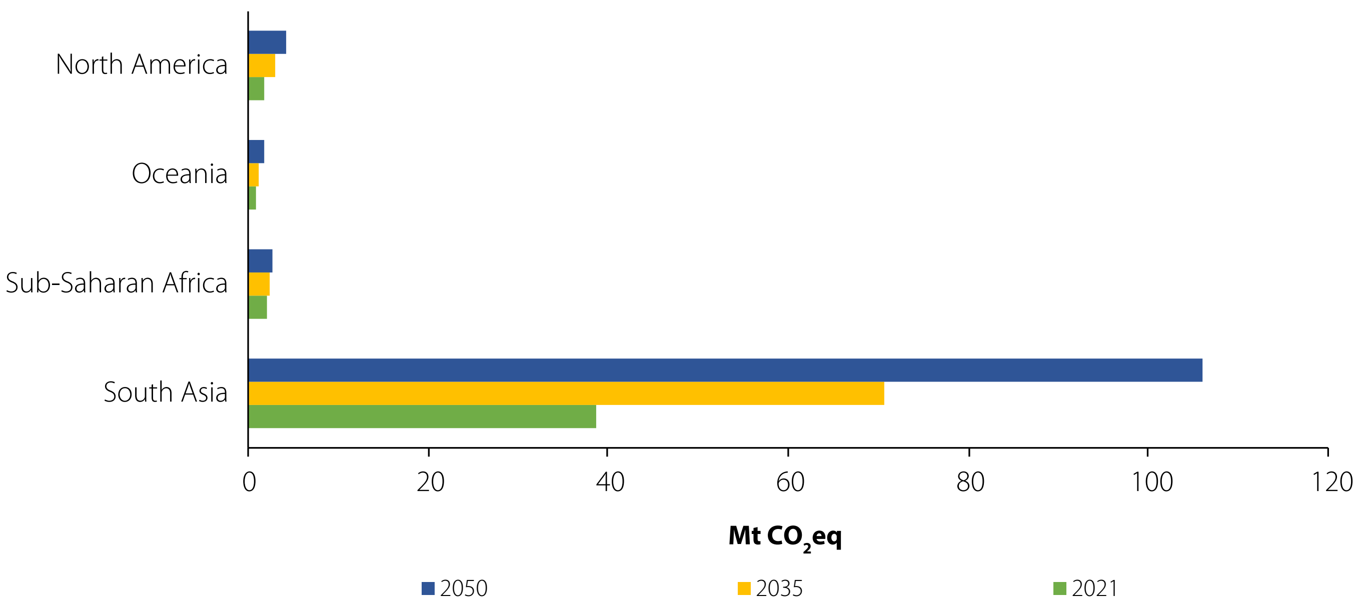
Figure 6 projects future global GHG emissions from both aquaculture and capture fisheries through 2050 under the *BAU* scenario based on extrapolated baseline data from MacLeod et al. (2020) and Parker et al. (2018). Global aquaculture emerges as an increasing contributor to total GHG emissions, with its share growing from 273.6 Mt CO_2eq in 2021 to a projected 497.4 Mt CO_2eq by 2050. This substantial rise reflects the anticipated rapid expansion of aquaculture in the future, underlying its growing environmental impact. In contrast, GHG emissions from capture fisheries remain relatively stable, with a nominal increase of 4.4 Mt CO_2eq, from 200.6 Mt CO_2eq in 2021 to 205.0 Mt CO_2eq by 2050. This suggests a comparatively steady environmental impact associated with capture fisheries, owing to stagnant production and limited expansion of this sector in the future.



Source: Author's computation from baseline data in MacLeod et al. (2020); Parker et al. (2018)

Figure 6. Projected global fish emissions from capture fisheries and aquaculture in 2021, 2035, and 2050.

Figure 7 presents the projected GHG emissions of aquaculture across North America, Oceania, SSA, and South Asia through 2050 under the *BAU* scenario, based on extrapolated baseline data from MacLeod et al. (2020) and Parker et al. (2018). A substantial increase is projected by 2035 and 2050 compared to 2021 across all of the regions, highlighting the growing environmental impact. In South Asia, aquacultural emissions are expected to more than double by 2035, increasing from 38.7 Mt CO_2eq to 70.8 Mt CO_2eq, and then rising another 50% by 2050 to reach 106.0 Mt CO_2eq. A similar trend is projected for North America, demonstrating moderate growth from 1.9 Mt CO_2eq in 2021 to 3.0 Mt CO_2eq by 2035, reaching 4.2 Mt CO_2eq by 2050. Although North America experiences a 120% growth over the projection periods combined, the scale of GHG emissions from aquaculture in North America remains much smaller than that of South Asia. In SSA, GHG emissions from aquaculture are expected to grow from 2.1 Mt CO_2eq in 2021 to 2.8 in 2050. Oceania follows a similar trend, with GHG emissions from aquaculture projected to increase gradually from 0.7 Mt CO_2eq in 2021 to 1.8 in 2050.



Source: Author's computation from the baseline data in MacLeod et al. (2020); Parker et al. (2018)

Figure 7. Projected aquaculture emissions for North America, Oceania, SSA, and South Asia in 2021, 2035, and 2050.

4. Discussion

The three investigated scenarios paint very different pictures of the future of fish production and consumption across the globe. In the *High* scenario, investment in green technology, enhanced international cooperation, and overall sustainable development lead to higher GDP growth than in the *Risk* scenario. Additionally, targeted investments in education and health trigger a considerable decline in population growth under this scenario. Compared to the *Risk* scenario, the *High* scenario presents significantly lower population growth in the future projection period. Unimpaired population growth is closely linked to regional inequalities, natural resource depletion and heightened GHG emissions, diverging further from the targets of the SDGs and the Paris Agreement. The overall trend of declining population growth under the *High* scenario is primarily driven by substantial reductions within Africa and Asia. Historically, high population growth in Africa and SSA is projected to slow down significantly, alleviating pressure on natural resources and food production systems.

Under the *BAU* scenario, the total fish supply is projected to increase moderately, likely outpacing population growth, as global per capita fish consumption is expected to advance. On the contrary, the *Risk* scenario displays fast population growth and limited fish production, resulting in reduced per capita fish consumption by 2050. The increase in fish supply until 2050 is projected to be lower than in the *BAU* scenario, as limited environmental concerns and slow technological progress hinder production growth. Although the alternative scenarios in this study do not include capture fisheries, it is essential to note that pessimistic climate *Risk* scenarios, as those connected to SSP 3 are linked to declining ocean productivity (Bindoff et al., 2019) and threats to aquaculture (Yadav et al., 2024; Zougmoré et al., 2016). The destabilization of fish production systems under the *Risk* scenario results in significant lagging compared to the *BAU* and *High* scenarios, evoking persistent challenges in this pathway in the coming decades. Among the studied regions, LAC and SSA show lower per capita fish consumption in 2050 than in 2019, marking the regional shortfall of fish supply in connection to rapid population growth. This trend is particularly concerning, as many vulnerable communities from SSA and LAC already face high levels of food insecurity and nutrient deficiencies (FAO et al., 2023; Muthayya et al., 2013). Besides being a major protein source, fish products contain crucial micronutrients such as vitamin A, calcium, iodine, zinc, iron, and selenium (Golden et al., 2021). Deficiencies in micronutrients contribute to "hidden hunger," which poses a burden for national health and economic growth, further exacerbating inequalities (Muthayya et al., 2013). The *Risk* scenario reinforces the persisting disparities in fish consumption between lower- and higher-income countries. Generally, increased per capita GDP correlates with higher per capita fish consumption, leading to above-average consumption of aquatic foods in North America and Oceania (FAO, 2023a, 2023c; Naylor et al., 2021; World Bank, 2023).

According to FAO (2024c), global aquaculture production surpassed capture fisheries for the first time in 2022. This finding is backed by our results, indicating the importance of aquaculture for future fish supply and the limitations of the capture fishery sector due to overexploitation and climate impacts. Nevertheless, under the *BAU* scenario, annual growth rates of aquaculture are projected to slow from 5% during the period from 2000 to 2021 to just 1.5% from 2036 to 2050. This slowdown is attributed to several factors, including stricter environmental regulations and enforcements, land and water scarcity, and disease outbreaks linked to intensive farming practices (FAO, 2022b). In the *Risk* scenario, global aquaculture is expected to produce 13.2% less fish than in the *BAU*, causing negative growth in certain regions until mid-century. On the other hand, strong economic growth coupled with manageable climate challenges under the *High* scenario create enabling conditions for investments into aquaculture development.

Although many regions have yet to explore their full aquaculture potential, Asia, particularly the ASEAN region and South Asia, are at the frontline of the global trend toward meeting seafood demand by mid-century. South Asia's fish production is expected to surge under the *High* scenario, surpassing the ASEAN's by 12.4 Mt in 2050. This growth could potentially address malnutrition and hidden hunger, as iodine and vitamin A deficiency remains prevalent in the region (Golden et al., 2021; Muthayya et al., 2013; Song et al., 2023). The *High* scenario further highlights the potential of aquacultural growth in Africa, especially SSA. To reach the current global fish per capita consumption of 20.3 kg, Africa will require additional 30.1 Mt of fish supply to meet the domestic demand by 2050. According to Zougmoré et al. (2016), approximately 31% of Africa's land area is suitable for small-scale aquaculture, and over 13% could potentially qualify for commercial aquaculture production. The correlation between lower aquaculture growth and a larger urban population suggests that space might be a limiting factor. Therefore, regions with larger shares of rural population, for instance Africa and South Asia, hold greater potential for aquaculture development (World Bank, 2023). This indicates that targeted investment and policies could enhance aquaculture's role in food and nutrition security in these regions.

The comparison between the GHG emissions from various food commodities highlights the significant environmental impact of livestock, particularly beef, which outweighs all other food commodities. Beef accounts for an astounding 22,362 Mt CO_2eq of GHG emissions because of its high feed conversion rates and high release of extremely potent methane. In direct comparison to beef, pig, poultry, and lamb meat, aquatic foods feature relatively low GHG intensity. Fish are highly fertile and efficient feed converters, requiring only 13 kg of grains, whereas pork requires 180% more and beef a whopping 350% (Béné et al., 2015; Hall et al., 2011; MacLeod et al., 2020). This efficiency reduces the overall carbon footprint of aquatic food production.

As cattle production depicts the main source of GHG emissions in both Asia and Africa, a shift away from beef-heavy food production could result in overall lower food system emissions and healthier diets (TWI2050, 2018; Willett et al., 2019). In Africa, the aquaculture sector emits the least amount of GHGs when compared to livestock and capture fisheries, but it is expected to grow significantly in the coming decades. Currently, GHG emissions from capture fisheries in Africa are more than three times higher than those from aquaculture. However, projections indicate that as aquaculture develops, its emissions are likely to increase 80% by 2050. In contrast, emissions from capture fisheries are expected to stagnate, suggesting a shift in the continent's seafood production landscape.

Asia is currently and in future projections the largest aquaculture producer and, therefore, the main emitter of GHGs among the studied regions. Among the regions, South Asia stands out as a major aquaculture emitter by the middle of the century. The transitional phase presents opportunities to implement climate-smart and low-emission technologies to ensure sustainable growth. Similar to climate-smart agriculture, climate-smart aquaculture aims to boost output, improve resilience, and reduce the environmental footprint of aquaculture production (Ahmed & Solomon, 2016). As feed constitutes the main source of GHG emissions from aquaculture, improving the efficiency of feed could significantly reduce the climate impact (Stanford Center for Ocean Solutions et al., 2024; Zhang et al., 2024). For instance, replacing traditional feed as the main protein source with black soldier fly (BSF) larvae exhibits numerous environmental, nutritional, and economic benefits (Manyise et al., 2023; Mohan et al., 2022). BSF constitutes a nutritional, low-cost alternative to soybeans and fishmeal, with the ability to convert organic matter into nutrient-dense feed. Therefore, this form of biowaste management decreases organic pollution from decomposition and thus reduces GHG emissions from aquaculture (Limbu et al., 2022).

Biofloc technology offers a sustainable approach to minimize inputs and GHG emissions by turning waste into feed through the growth of bacteria, which also improves water quality (Dauda et al., 2019; Ogello et al., 2021; Zablon et al., 2022). Similarly, aquaponics are a promising form of low-emissions fish production in regard to land and water scarcity (Obirikorang et al., 2021; Yadav et al., 2024), as it combines fish farming with plant cultivation in a closed water system to reduce inputs and pollution (Baganz et al., 2021; Obirikorang et al., 2021). Recent studies confirmed the environmental benefits of the physical combination of rice and fish production (Wang et al., 2024). Despite being a plant-based product, rice cultivation emits comparably large amounts of GHGs (3,503 Mt CO_2eq), particularly N_2O and CH_4, making rice a significant source of emissions within food systems. Co-culturing rice and fish can reduce GHG emissions, as fish support the ventilation and oxygenation of rice paddies and aerate the soil (Wang et al., 2024).

Innovations like these, including integrating algae production into aquaculture for improved water quality and reduced feed demand (Yadav et al., 2024), can support sustainable intensification in high-emission regions. Policies in the blue economy could further target the energy source of aquaculture, promoting the usage of renewable energies and low-energy practices. Furthermore, the reduction of post-harvest losses and fish waste could have a major impact on fish availability, safety, and sustainability, as global food waste accounts for over 6% of GHGs (Stanford Center for Ocean Solutions et al., 2024).

Our projections indicate that the environmental impact from GHG emissions associated with capture fisheries remains steady, given the stagnant future production under the *BAU* scenario. Fuel combustion constitutes the major source of GHG emissions in capture fisheries, making interventions challenging (Gephart et al., 2021; Hornborg et al., 2020). Overfishing and targeting demersal species, which require more fuel, further increase emissions. Reducing fossil fuel use in fisheries can be achieved by focusing on healthier, smaller pelagic stocks. Optimizing fishing gear and transitioning to electric or hybrid fleets can help lower emissions and promote sustainable fishing practices (Gephart et al., 2021). Nevertheless, the environmental impacts of aquatic food production reach beyond GHG emissions. Capture fisheries are responsible for overexploitation of fish stock and habitat degradation, particularly of benthic ecosystems, as well as marine pollution in the form of lost and discarded fishing nets, among other factors (FAO, 2024c; Jesintha & Madhavi, 2020). On the other hand, aquaculture production contributes to the deforestation of mangrove forests (Ahmed & Glaser, 2016), eutrophication, the release of non-native and genetically modified species (Jeanson et al., 2022), larger amounts of water and energy consumption, and high feed inputs from fisheries, livestock, and crops (Jiang et al., 2022).

We addressed the challenges posed by inconsistent and limited fish emission factor metrics from aquaculture and capture fisheries at the regional and national levels. In follow-up studies, we will gather additional insights through stakeholder consultations to include an analysis of alternative scenarios for capture fisheries, and to extrapolate future GHG emissions of fish under the two alternative scenarios, *High* and *Risk*, across the different regions under the study. By leveraging expert assessments gathered during stakeholder consultations, we aim to better understand the potential pathways for reducing GHG emissions in both capture fisheries and aquaculture, tailored to specific geographic contexts. This approach will help identify region-specific interventions and strategies for achieving low-emissions fisheries and aquaculture practices.

5. Conclusions

Our projections show the growing importance of aquaculture around the globe and the overarching benefits of sustainable development and a low-emission pathway. Following global trends of marine biomass reduction and the disappearance of commercially targeted aquatic species, the production of capture fisheries stagnates around its 2021 levels. In contrast, aquaculture is poised for significant growth, particularly in South Asia and SSA, where combined emissions are projected to reach 108.8 Mt CO_2eq by mid-century. Despite lower emissions from fish production compared to other livestock, due to its high feed conversion efficiency, the expected rise in aquaculture emissions by 2050 highlights the need for climate-smart, integrated solutions to manage this growth sustainably. Our projections emphasize the *High* scenario as the most desirable outcome, featuring the least climate-related challenges, moderate population growth, global prosperity, and improved food security. Although fish production alone cannot solve the global food system's emissions challenges, complementing livestock protein with fish protein could enhance both planetary and human health. Achieving these outcomes will require investments in research, technology, monitoring, and management, particularly in sustainable aquaculture practices. This comprehensive approach offers a strong foundation for policy discussions on reducing GHG emissions and promoting sustainable aquatic food systems.

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About WorldFish

WorldFish is a leading international research organization working to transform aquatic food systems to reduce hunger, malnutrition and poverty. It collaborates with international, regional and national partners to co-develop and deliver scientific innovations, evidence for policy, and knowledge to enable equitable and inclusive impact for millions who depend on fish for their livelihoods. As a member of CGIAR, WorldFish contributes to building a food- and nutrition-secure future and restoring natural resources. Headquartered in Penang, Malaysia, with country offices across Africa, Asia and the Pacific, WorldFish strives to create resilient and inclusive food systems for shared prosperity.

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