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Economics of Fisheries and Aquaculture and Sustainable Practices for Long Term Resource Use

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Abstract: Fisheries and aquaculture form crucial pillars of food security, employment, and trade globally, contributing over US$401 billion to the global economy and providing livelihoods to over 600 million people. This analysis analyzes the economics of fisheries and aquaculture combined with the environmental sustainability necessary for future preservation. Utilizing global production data, bioeconomic theory, and policy analysis, the paper addresses existing trends of economic status, inefficiencies derived from the underpricing of ecosystem services, and policy implications of key instruments such as rights-based management, certification schemes and integrated multi-trophic aquaculture. We find that capture fisheries reached maximum revenues of US$162.5 billion in 2003, while aquaculture reached US$214.8 billion and growing annually by ~6%. When comparing profitability, differences arise between varying production systems: while intensive, recirculating, aquaculture systems achieve greater productivity they also attain the greatest capital cost whereas polyculture and integrated systems achieve optimal sustainability measures. Overall, the evidence demonstrates a conflict between short-term economic interests and long-term environmental sustainment and thus requires a change towards ecosystem-based fisheries management and optimization of value chains. Our policy implications include enhanced subsidy reform, extended economic buffers around marine protected areas, stimulating participation in eco-certification schemes, and developing climate-adapting technology.

Keywords: Bioeconomic Modeling; Aquaculture Sustainability; Fisheries Economics; Ecosystem Services Valuation; Rights-Based Management; Resource Governance.

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I. Introduction

Fisheries and aquaculture are the most important economic activities among other activities within blue economy, which serve food supply system, generation of foreign income and employment for rural areas of inland and coastal areas of the world. About 183.3 million tons of aquatic products were produced with a first sale value of above 401 billion dollars (USD) (2022) according to Food and Agriculture Organization of United Nations Maunder & Piner (2015), of which there were only direct contribution for economy (food processing, logistics, retail trades, ecotourism). As the environmental limits are becoming more apparent and demand are expanding globally, there are increasingly close examination to governing systems and economic structures of fisheries and aquaculture. Fish stock depletion, byproduct and environmental damages are endogenous problems in capture fisheries, which is exacerbated by open access regime; fish culture systems are also subject to increasing concern with regards to their environmental impacts, diseases risks and social license. These concerns reflect themselves economically through inefficiencies of resource allocation, under-investment in sustainable technologies, and price signals that disregard to their full costs of environmental damage (Naylor et al., 2021; Asche et al., 2018).

Moreover, aquaculture has been grown as the fastest food production industry worldwide and surpasses capture fisheries for human consumption in total volume since 2014, driven by improvement of technology for managing fish hatcheries, animal nutrition, breeding, and diseases control and increasing demand from medium and high-income population for protein rich seafood within Asia, Latin America and sub-Saharan Africa (Troell et al., 2023). However, it has been characterized by fragmentation at small-scale and industrial operations, and considerable variations in productivity, market access and environmental performances.

Economic analysis for fisheries and aquaculture systems has significantly changed from traditional static maximum sustainable yield (MSY) to dynamic bioeconomic models integrating the stocks dynamics with economic behavior under uncertainty in the last decades (Punt et al., 2015). Recently, ecosystem-based approaches have been developed integrating ecosystem interactions, dependency on environment and climate condition into bioeconomic models, that assumes the fisheries and aquatic resource system as complex adaptive systems rather than simpler fisheries system in terms of single fish species harvested (Hilborn et al., 2020; Egash & Teyene, 2023).

The paper, with focus on the application of sustainable practices which help the long-term sustainability of aquatic resources, summarizes current understanding of the economics of capture fisheries and aquaculture. Analysis is based on global statistical data, reviewed bioeconomic analyses, institutional studies and emerging results derived from both rights-based fisheries management and fish certification schemes. Specific aims of the study are:

- Characterizing the world economic organization of fisheries and aquaculture.
- Identification of factors driving profitability and investment through production systems.
- Assessing the economic efficiency of sustainability instruments.
- Identification of policy pathways toward an economic environment consistent with ecological sustainability.

The paper is organized as follows. The first section discusses the economic importance of the fisheries and aquaculture sectors, provides statistics of the world production and revenue, and addresses problems related to the inefficient markets and resource limitations that fisheries and aquaculture face. In the second section, materials and methods-data and inputs, bioeconomic framework and model, performance and sustainability indicators, and the comparative policy assessment methodology are described. Section 3 provides the results concerning the structure of global economy, profit and efficiency, performance and the effectiveness of instruments of sustainability. Those are demonstrated by use of tables and figures. In the fourth section, the results of the mechanisms of the ecological and economic processes, sector-specific problems, and policy implication on managing the fisheries and aquaculture to promote sustainability are explained. Finally, in the fifth section the paper concludes on research findings, policy recommendation and future research priorities to sustain fisheries and aquaculture economy ecologically and economically for the long-run.

II. Materials and Methods

Data Sources and Scope

This work utilizes a range of secondary data from recognized sources such as the FAO Global Fishery and Aquaculture Production Statistics database (FishStatJ 2024 edition), World Bank WAVES partnership datasets regarding natural capital accounting, the certification database from the Marine Stewardship Council (MSC) and the Aquaculture Stewardship Council (ASC), and International Monetary Fund commodity price indices for fishery products (Punt, 2019). Data from peer-reviewed articles from 2018-2025 were also utilized. The research covers a global production systems analysis and five regional case-specific analysis, on capture fisheries on North-East Atlantic; small-scale mixed fisheries on South-East Asia; salmon aquaculture on the Norwegian fjords; freshwater polyculture on the delta of Bangladesh; and offshore integrated mariculture on Baja California. These case studies represent various different economies, production scale, ecological governance arrangements.

Figure 1 demonstrates the system of interrelationships within global fisheries and aquaculture sectors in economic and ecological context. Production systems are defined as the foundation of outputs and returns from the sectors: capture fisheries, sub-sectors of aquaculture and the mixed systems.

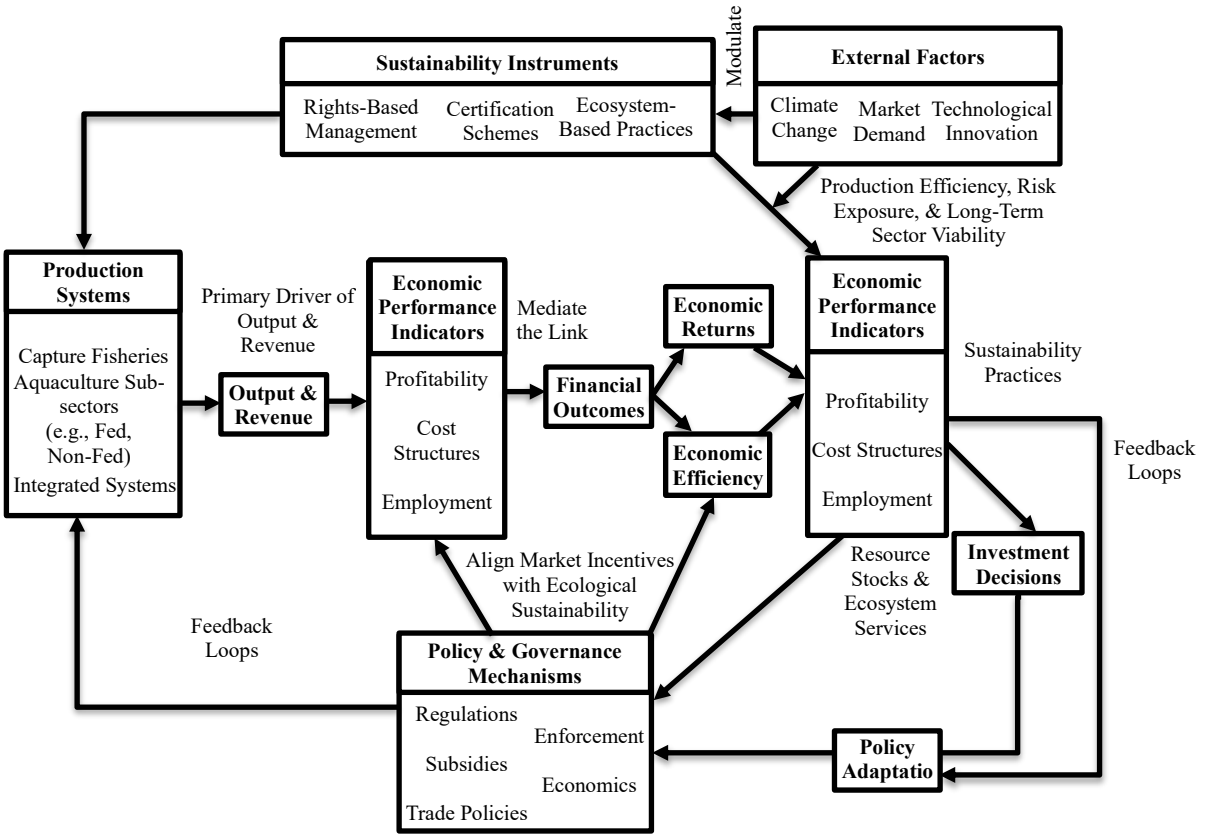


Figure 1: Global Fisheries and Aquaculture: Economic Ecological Conceptual Framework

Economic viability indicators (profitability, costs, jobs) transmit this flow between production systems and results of activities. Economic sustainability instruments such as rights-based management, certification and ecosystem-based approaches contribute to ecosystem services and economic performance at the same time. Policy and governance tools are employed to harmonize the incentive structure for the market with sustainability goals. Environmental and external drivers such as climate change, market demand and technical innovation affect production efficiency, risk and sector's long-term sustainability. Feedbacks indicate the impact of improved ecological efficiency on resource stocks and ecosystem services, and thereby influencing economic outcomes and investment patterns.

Bioeconomic Framework

To explore the linkage between fishing effort, resource rent, and sustainable yield in capture fisheries, an adjusted Gordon-Schaefer bioeconomic model was employed. The standard Gordon-Schaefer model is given as (Equation 1):

$$\pi = \frac{p \cdot q \cdot E \cdot K}{r}\left(1 - \frac{qE}{r}\right) - cE \quad (1)$$

Where Y is yield; p, price; q, catchability coefficient; E, effort; K, carrying capacity; r, intrinsic growth rate; and c, unit cost of effort (Pitcher & Preikshot, 2001). The model was adjusted to include price-elastic demand and dynamic adjustment in stock-effort relationships to find short and long-run equilibria. A partial equilibrium model with cost-benefit relationships at the farm level, summed over the scales of production, was applied to aquaculture. Costs were categorized as variable costs (feed, seed, labor and energy) or fixed capital investment to determine breakeven production levels and returns on investment under both the standard and the alternative strategy cases.

Sustainability Indicator Assessment

Sustainability was assessed using a multi-attribute index with five dimensions: ecosystem integrity (stock condition and habitat status), economic efficiency (cost and profit competitiveness), social equity (income equity and gender equality), governance effectiveness (rule of law, governance and participation) and climate vulnerability (resilience and carbon intensity). Each attribute was graded on a common scale of 0-10 following previously accepted scoring schemes and based on the principles of UN's Sustainable Development Goals (Costello et al., 2016). Expert elicitation method with iterations through Delphi rounds was used to derive the weighting scheme.

Policy Analysis

Comparison of the relative effectiveness of different management instruments was accomplished by undertaking a systematic literature review of empirical studies evaluating the effectiveness of fisheries management instruments, published from 2015 onwards. Data was synthesized using a narrative synthesis approach and findings triangulated with grey literature from international organizations such as the FAO, World Bank, and the OECD. Where quantitative outcome data was available, effect sizes were standardized in order to facilitate comparisons between studies.

III. Results

Global Economic Structure of Fisheries and Aquaculture

Overall, world fisheries and aquaculture output during 2023 was around 225.6 million tonnes with an estimated first-sale value (FSV) of $401.5 billion. Of this total, capture fisheries provided 92.4 million tonnes (40.9 %) and aquaculture 130.9 million tonnes which includes aquatic plants (Buschmann et al., 2017). In terms of the economic contribution to the sector as a whole, the share for aquaculture has increased to an estimated 53.5 % despite many commodity species commanding a lower price per unit. Comparative data across some of the key production sub-sectors is given in table 1.

Table 1: Comparative Economic Indicators Across Major Fisheries and Aquaculture Sub-Sectors (2023)

Sector / Indicator	Global Production (million tonnes, 2023)	Economic Value (USD billion, 2023)	Employment (million people)	Annual Growth Rate (%)	Sustainability Index (0–10)
Marine Capture Fisheries	80.3	162.5	38.6	0.8	5.2
Inland Capture Fisheries	12.1	18.4	11.2	1.2	4.8
Marine Aquaculture	36.1	89.6	12.4	5.7	6.3
Freshwater Aquaculture	57.8	113.2	24.7	6.4	6.1
Integrated Systems (IMTA)	4.2	11.8	1.8	9.2	8.1
Seaweed/Algae Farming	35.4	16.5	3.2	7.1	8.6

The bulk of the total production (57.8 Mt) was freshwater aquaculture, the bulk of which was accounted for by Chinese carp polyculture systems. The balance was 36.1 Mt of marine aquaculture. High per-unit values for marine aquaculture are associated with higher value species (salmon, sea bream, sea bass) and molluscs. The smallest relative increase by volume (9.2%) but high growth is in integrated multi-trophic aquaculture (IMTA), illustrating the growing use of nutrient cycling and waste valorization in the industry. Growth rates for seaweed/macroalgae production were also high (7.1%/yr), driven by growth in demand by food, pharmaceutical and bioenergy industries (Bergh et al., 2001).

The largest sector with respect to jobs relative to economic value is inland capture fisheries where 11.2 million workers were directly employed to generate $18.4 billion dollars of value. High labor to value

proportions in inland capture fisheries reflect their capital poor, labor-intensive, small-scale nature in South and SE Asia, and the predominance of livelihood driven participation rather than that associated with cash profit. Higher capital to labor ratios is apparent in large scale salmon culture and industrial marine capture fisheries.

Profitability and Economic Performance Indicators

Figure 2 shows trends in profitability of the dominant production systems from 2015-2023, and demonstrates distinct trends for the aquaculture and capture fisheries sub-sectors. The operation margins of large-scale salmon farming system remained at the highest levels (average of 24.3% over the period), which are resulted from beneficial price premiums, improving feed conversion, and market access to valuable export markets (Sumaila et al., 2019). In the meanwhile, the operation margin of the shrimp farming system showed much larger fluctuations because of the recurrence of disease outbreaks, including the ones in Penaeusvannamei (EMS and WSSV), and the feed costs fluctuations, with an average operating margin of 8.7% with high inter annual variations.

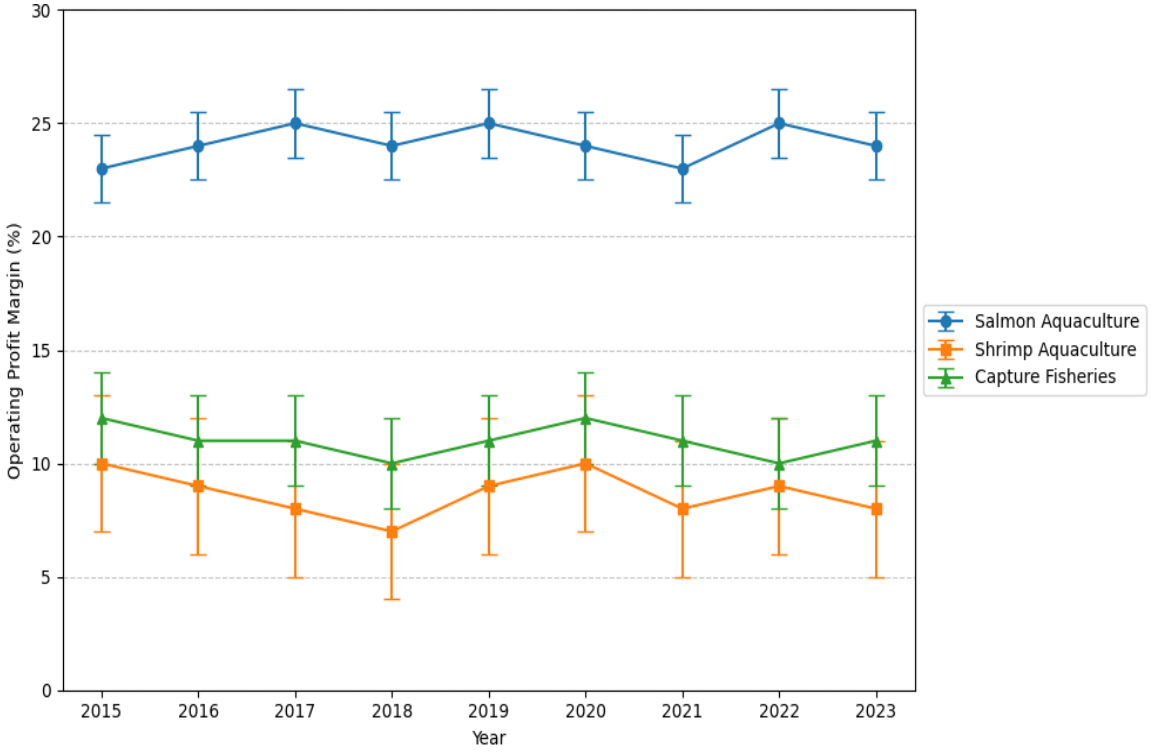


Figure 2: Operating Profit Margins Across Fisheries and Aquaculture, 2015–2023

A considerable fall in profitability in the capture fisheries has occurred for many demersal species such as North Atlantic cod, Pacific hake and Indian Ocean tuna, due to overfishing and a depleted resource base that result in an unprofitable return on effort (Badiola et al., 2018). In small pelagic fisheries where anchovy, sardine and herring are harvested with the economy- of-scale argument that they can be harvested cheaply in huge volumes, margins remained positive however prices were subject to significant risk owing to their correlation with fishmeal prices (Badiola et al., 2018).

Recirculating aquaculture systems showed high productivities (80-150 kg/m), however high capital requirements made these systems expensive to build with installation costs of $1.2-3.8 million per t production capacity. Return on investment periods for these systems varied between 6 and 14 years, dependent upon energy costs, the species produced and market access. It is therefore predicted that the implementation of RAS will take place predominantly in regions with low energy costs, stable political frameworks and easy access to well-populated and affluent areas (Fujita, 2021).

Sustainability Instrument Effectiveness

A comparative sustainability assessment highlighted substantial variation in index scores between sub-sectors (Table 1). IMTA and seaweed systems attained the highest overall sustainability indices of 8.1 and 8.6, respectively. Waste recycling, nutrient sequestration and reduced external feed requirements are key reasons for their performance. Conventional intensive marine aquaculture ranked lowest at 6.3, influenced largely by environmental footprint metrics, such as nitrogen loading, impacts on the benthos and application of antibiotics. Average overall scores for marine capture fisheries and aquaculture were 5.2 and 7.0 respectively, while performance in marine capture fisheries was highly variable, differing substantially between certified and uncertified fisheries.

Evaluation of the impact of certification showed that MSC-certified fisheries were statistically more sustainable at the stock level, and had a lower frequency of IUU fishing when compared to uncertified fisheries (De Melo et al., 2024). However, high-income industrial fisheries were more readily certifiable, and there was a pronounced tendency for industrial-scale fisheries in developed countries to adopt certification over small-scale, data-poor fisheries operating within regions at the highest ecological risk. ASC certification on aquaculture operations resulted in better performance in environmental indicators, where certified operations showed 34% and 22% lower intensity of nitrogen discharge and antibiotic usage respectively in relation to controls. It was observed that RBM instruments produced the strongest evidence of improved economic efficiency gains, where ITQ fisheries generated an average of 18-24% greater net economic rents than effort-controlled counterparts. In the same sector, there are persistent equity concerns where the initial distribution of quotas often favored large-scale operators, undermining equity dimensions of social sustainability and leading to rural inequity in fishing communities.

IV. Discussion

The results of this analysis further strengthen the underlying economic dilemma inherent in fisheries and aquaculture: short-term, profit-maximizing behavior under open-access or weak governance regimes leads to resource overexploitation and the eventual deterioration of the sector's biological and economic resource base. This problem, first modeled formally by Gordon in the original economics of a fishery article, remains a crucial element in numerous diverse contemporary production environments, ranging from artisanal tropical fisheries to industrial high seas fishing. The strong economic performance of certified and rights-based fisheries illustrates how strongly institutions matter in determining economic outcomes. Well-structured governance systems that confer clear, exclusive and transferable access rights effectively internalize externalities that otherwise remain unaddressed in open-access situations, and thereby align individual incentives with collective goals of resource sustainability. The economic rents recaptured under ITQ systems in Norway, Iceland and New Zealand demonstrate how well-designed property rights can generate significant economic value while also enabling stock recovery and stability of production.

Aquaculture sustainability is a more complex yet equally significant economic problem. While the sector's phenomenal growth has spurred both food security and economic gains, concentration of production into just a few species in intensified systems poses systemic risks that range from vulnerability to disease to limits of feed supply and environmental carrying capacity. The robust economic performance in the sustainability index scoring attributed to IMTA and polyculture shows the potential for economically beneficial integration of diversity that enhances ecological efficiencies and delivers valuable system co-benefits. The failure of economists to adequately value ecosystem services in the study of fisheries and aquaculture economics is a persistent, structural flaw with considerable implications for resource allocation. Coastal nursery habitats, water quality regulation, carbon sequestration and cultural services underpinning productive fisheries are often missing from sector analyses, creating incentives to eliminate them in favor of activities that deliver measured private economic returns. Integrating natural capital accounting into fisheries economics must therefore be considered not an arcane analytical modification, but a requirement of sensible natural resource management.

Climate change is an increasingly important factor modifying fisheries and aquaculture economics; its effects species distribution, phenology, productivity regime, and frequency of extreme events that disrupt operations. Models that fail to account for climate dynamics will underestimate both future yields and adaptation costs, leading to inefficient allocation of investment and policy decisions. Bioeconomic modeling under Representative Concentration Pathway scenarios predicts that global marine fisheries revenue could be reduced by between 10-35 % by 2100 under business-as-usual high-emission pathways, with the greatest proportional impacts on tropical developing nations which are more reliant on fisheries for food security.

Small-scale and artisanal fisheries warrant special consideration in sustainability-oriented economic models. Such fisheries support majority of global fishing employment, provide local food sources, retain cultural value and harbor ecological knowledge with conservation implications. However, they suffer systematically from prevailing market structures, certification costs and regulations designed around large-scale industrial operations. Economically inclusive sustainability transitions will thus need to build in different policy instruments specific to their capacity constraints and abilities.

V. Conclusions

The economic viability of fisheries and aquaculture depend critically on the health of the aquatic systems where they are conducted; sustainable fisheries and aquaculture management is not simply an environmental imperative, but an economic one. Highlights from this report confirm that the aquaculture industry is already the most valuable in the sector globally and continues to grow much faster than capture fisheries, the latter being central to food security and livelihoods for people in the developing world. Rights-based fisheries management and third-party certification schemes are arguably among the most empirically proven means to enhance the economic efficiency of capture fisheries as well as ecological sustainability, although safeguards need to be applied to these measures to protect small-scale actors from being further disadvantaged. Regarding aquaculture, the environmental sustainability performance of integrated, low-input systems is among the highest and these systems are anticipated to become increasingly economically competitive as the role of environmental external costs in accounting and regulation becomes better defined. The policy priorities recommended for a sustainable fisheries and aquaculture economics sector were the following: removal of perverse subsidies in fisheries, reinvesting that money into monitoring, surveillance and management of marine resources, enforcement and community-based management. Integrated Marine spatial Planning should be developed to decrease conflicts between various sectors involved and to help protect important aquatic habitats; data infrastructure needed to inform fisheries management practices where information is lacking in poor data countries; funding to allow fishing communities and small-scale aquaculture operators to adapt to climate change. Further research should investigate the application of machine learning and remote sensing technologies to provide real-time economic monitoring of bio-resource productivity, the development of equity-adjusted welfare measures for assessing sustainability; and an empirical analysis of payments for ecosystem services as a complement to traditional instruments.

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Conflict of Interest

No competing interest was declared by the authors.

Data Availability Statement

All data used for the findings of this study are public available from the references mentioned below.

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