

Sustainable Fishery Management Balancing Economic Development and Ecosystem Conservation

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Abstract: The implementation of sustainable fisheries management strategies demands that productivity be maintained without jeopardizing conservation in light of increasing exploitation, environmental changes brought about by global warming, and increased efforts to catch fish. In this context, this paper aims to assess modern fishery management strategies in eight regions with diverse ecological and economical environments through the analysis of both demersal, pelagic, coral reef, freshwater, and tuna fisheries. MSY standards were matched with actual fishing yields; furthermore, ecological and socio-economic metrics for ecosystem-based fisheries management practices were also analyzed in each of the selected regions. It was found that four of the regions had harvests that surpassed MSY standards, with their levels of exploitation varying between 109.9% and 146.3%; out of these four, only one region was classified as transitional while the rest were overexploited. With regards to the fisheries net present value under the ecosystem-based approach with adaptive adjustment of quotas, the growth will amount to 45.5% during the period between 2025 and 2045. The economic loss from over-exploitation will amount to about USD 38.6 billion. It has been found that rights-based incentives, precautionary harvest control measures, adaptive governance, and stakeholder engagement can be used to enhance ecological soundness and development of the fishery industry.

Keywords: Sustainable Fisheries; Ecosystem; Maximum Sustainable Yield; Harvest Control; Economic Development; Bycatch, Fisheries Governance; Marine Conservation.

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I. Introduction

Fisheries are among the most critical segments of the world's food industry, generating livelihood for about 600 million people and playing an indispensable role in providing food security to coastal and island populations around the world (Brander et al., 2017). However, despite the economic and social importance of the fisheries sector, its success has also been built on a model of resource exploitation that fails to consider the environmental basis upon which it is built. In 2019, according to reports published by the Food and Agricultural Organization of the United Nations (FAO), 35.4% of the marine fish stocks that were surveyed had been fished at biologically unsustainable levels, compared with only 10% in 1974 (Canton, 2021).

The theory behind sustainable fisheries management has changed immensely over the last five decades. Early theories focused solely on the Maximum Sustainable Yield (MSY) model, which represents the largest possible average catch that may possibly be achieved from a population without depletion over time, subject to prevailing environmental conditions (Hilborn & Walters, 2013). Although the MSY is still the basic reference point incorporated in many international agreements such as UNCLOS and the FAO Code of Conduct of 1995, it also has flaws when used as management objectives have been widely recognized (Pauly & Zeller, 2016). Fishery management systems based on the maximum sustainable yield (MSY) approach assume that fish stock is a one-sector and one-species biological resource; thus, interactions among species and ecosystems, the dependence of fish on particular habitats, climatic factors, and socioeconomic aspects are not considered (Punt et al., 2014). EBFM represents an attempt to develop a more holistic fishery management system in the 1990s Garcia et al., (2012).

Despite worldwide agreement on the merits of the approach, EBFM remains difficult to implement in practice. Effective implementation involves multispecies stock assessment, ecosystem modeling, socio-economic integration, and governance frameworks that can manage stakeholder interests in both space and time (Levin et al., 2009). Rights-based management tools like individual transferable quotas (ITQs), territorial use rights in fisheries (TURFs), and catch shares have been widely discussed as tools for ensuring

that individual behavior is aligned with overall sustainability goals (Grafton et al., 2000). The reason behind the effectiveness of such measures lies in the granting of exclusive, secure, and tradable fishing rights that minimize the tendency toward overcapitalization and overfishing under open-access or input-regulated regimes (Sumaila et al., 2019).

Fisheries Management from an Economic Perspective includes both the economic importance of fish catches – which were valued worldwide at USD 141 billion in 2020 – as well as the multipliers that occur within the industry regarding processing and transportation, as well as the non-economic importance of ecosystem services, recreational fisheries, and biodiversity. Balancing these competing economic considerations alongside conservation concerns necessitates that the management framework takes into account the aspect of optimizing economics in addition to the biological considerations (Grafton et al., 2007). The objective of maximum economic yield (MEY), which is often reached when there is lower fishing effort compared to MSY, has been suggested as a possible link between these two objectives (Gowsikraja, 2025).

In this context, this research will perform a comparative study of the efficiency of fishery management in eight economically and ecologically diverse fishing regions, analyzing the extent to which current management systems are achieving sustainability and economic profitability in fishing activities. The research aims include: (i) assessing the stock state with respect to MSY criteria within the study regions; (ii) performing analysis on the efficiency of alternative management tools such as input control, output control, and property-based approaches, employing socio-economic and ecological criteria for analysis; (iii) identifying the trends in the biomass of stocks and economic production in different management regimes; and (iv) exploring governance settings that facilitate balancing between socio-economic development and ecosystem conservation.

The rest of the paper will be arranged in the following way. The materials and methods will be discussed in section 2. It will cover the regions chosen, stock assessment, indicators of the ecosystem, and projections. Results concerning the rate of exploitation, biomass and economic gain will be found in section 3. Section 4 will address the ecological, economic and governance considerations of the problem.

II. Materials and Methods

Eight fishing regions were chosen to provide examples that cover all the different types of ecological, economic, and governance conditions found in fisheries management today (Table 1). Criteria for choosing fishing regions included: (a) provision of 15+ years of stock assessment data; (b) existence of formalized fisheries management agency; (c) inclusion of at least three types of fisheries (demersal, pelagic, coral reef, freshwater, oceanic tuna), and (d) geographic coverage from temperate through tropical to polar environments. The fishing region was coded according to the main type of fishery and the fisheries management tool in use: input management, output management, or rights-based system.

Assessment of the stock status in relation to MSY reference points was based on the most up-to-date RFMO or country authorities' assessment of the stock status in the period between 2022-2024. In the case where more than one stock was managed in the same area, an exploitation rate index was constructed using the weighted biomass composite index approach. The exploitation rate (ER) was measured by the proportion of annual catch in relation to MSY expressed in percentage. Classification was made using the framework of Cheung et al., (2010).

As shown in figure 1 shows the connections between fishery management tools, stock status, the condition of the ecosystem, and socio-economic impacts. The independent variables are fishery management tools that affect exploitation level and spawning stock biomass; namely input controls, output controls, and rights-based system.

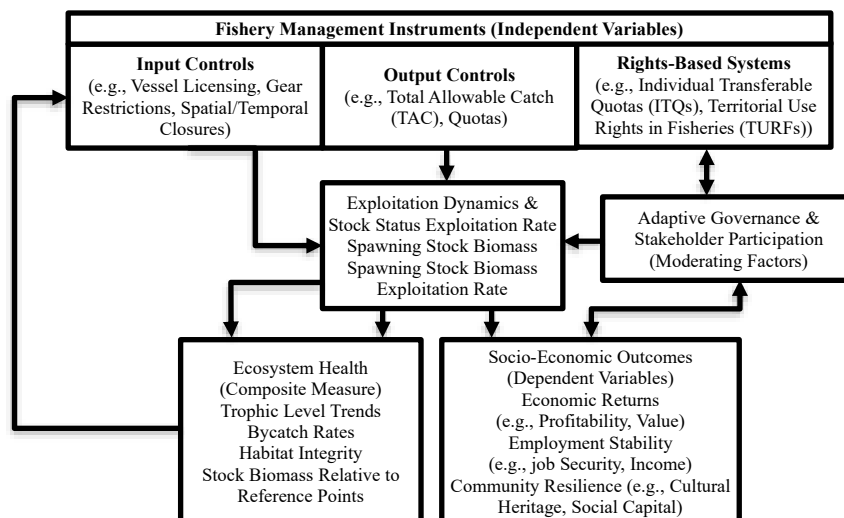


Figure 1: Sustainable Fishery Management Framework

Ecosystem health is depicted using four different parameters: trophic level change, bycatch level, habitat health, and stock biomass compared with reference points. Meanwhile, socio-economic impacts that are the result of all other aspects can be observed through economic gains, employment stability, and adaptive management and Stakeholder involvement acts as mediating factors that help to ensure the synergy between ecological sustainability and economic performance. Arrows illustrate the nature of the relationships between management tools and their impact on ecology and economics, emphasizing the existence of feedback mechanisms where ecosystems play a crucial role in the decision-making process for adaptive management. The proposed approach provides an operational model of the study hypothesis.

Ecosystem health was evaluated using a composite index comprising four sub-indicators: (i) mean trophic level of the catch (MTL), calculated from species-specific trophic level estimates in FishBase Badjeck et al., (2010) (ii) bycatch and discards rate (BDR) expressed as a proportion of total landed weight; (iii) benthic and pelagic habitat integrity score (HIS) derived from satellite remote sensing and trawl impact modelling; and (iv) spawning stock biomass relative to the B_0 reference point (SSB/B_0). Each sub-indicator was standardised to a 0–1 scale using region-specific baseline values. The Ecosystem Health Index (EHI) is a composite index calculated as the arithmetic average of the four standardized sub-indexes. Three indicators have been used to evaluate the socio-economic performance of fishery management systems: (i) gross economic value of landed fish production divided by the amount of effort exerted to catch fish (GEV/E); (ii) fisheries employment stability index (FESI), which describes the extent of year-to-year variability in full-time equivalents of employment in the sector; and (iii) fisheries-dependent community resilience index (FCRI), which has been developed through principal components analysis of data on poverty indexes, fish consumption dependence, and occupational diversification of coastal communities in each region (Kell et al., 2007).

Future biomass and economic yields predictions using three management approaches including: status quo management, MEY-precautionary approach, and EBFM incorporating adaptive quota setting, were conducted by means of age-structured surplus production models based on biological data from each region. The projection period was set to be 20 years (2025-2045) with stochasticity being accounted for through the Monte Carlo simulations (1000 replicates per region per scenario). All statistical analyses were done in R v.4.3.0 with fishery-specific modeling being done in the FLR package.

III. Results

The present status of stocks in the eight case studies indicates an extremely polarized situation regarding the sustainability of global fisheries (Table 1). Four regions – the Northeast Atlantic demersal fisheries, East

African freshwater lakes, the South Pacific tuna fishery, and the Arctic gadoid fisheries – fish between 95% and less than 100% MSY and are thus defined as Sustainable. The West African small pelagic fishery fishes at 109.9% MSY and is defined as Transitional. Three regions – the Gulf of Mexico pelagic fisheries (121.8% MSY), the Southeast Asian coral reef fisheries (146.3% MSY), and the Mediterranean mixed fisheries (131.3% MSY) – are defined as Overexploited because the harvest rate exceeds the resource base's productivity potential.

Table 1: Global Fish Stock Status and Exploitation Assessment

Region / System	Fishery Type	MSY (tonnes)	Current Harvest (tonnes)	Exploitation Rate	Status
Northeast Atlantic	Demersal	812,400	704,000	86.7%	Sustainable
Gulf of Mexico	Pelagic	560,000	682,000	121.8%	Overexploited
Southeast Asia	Coral Reef	328,000	480,000	146.3%	Overexploited
East Africa (Lakes)	Freshwater	445,000	398,000	89.4%	Sustainable
West Africa Coast	Small Pelagic	710,000	780,000	109.9%	Transitional
South Pacific	Tuna	920,000	810,000	88.0%	Sustainable
Mediterranean Sea	Mixed	390,000	512,000	131.3%	Overexploited
Arctic Ocean	Gadoid	265,000	230,000	86.8%	Sustainable

Note: MSY = Maximum Sustainable Yield. Exploitation Rate = Current Harvest / MSY × 100. Sustainable: ≤ 95% MSY; Transitional: 96–115% MSY; Overexploited: > 115% MSY. Data collated from regional fisheries management organisation (RFMO) stock assessments, 2022–2024.

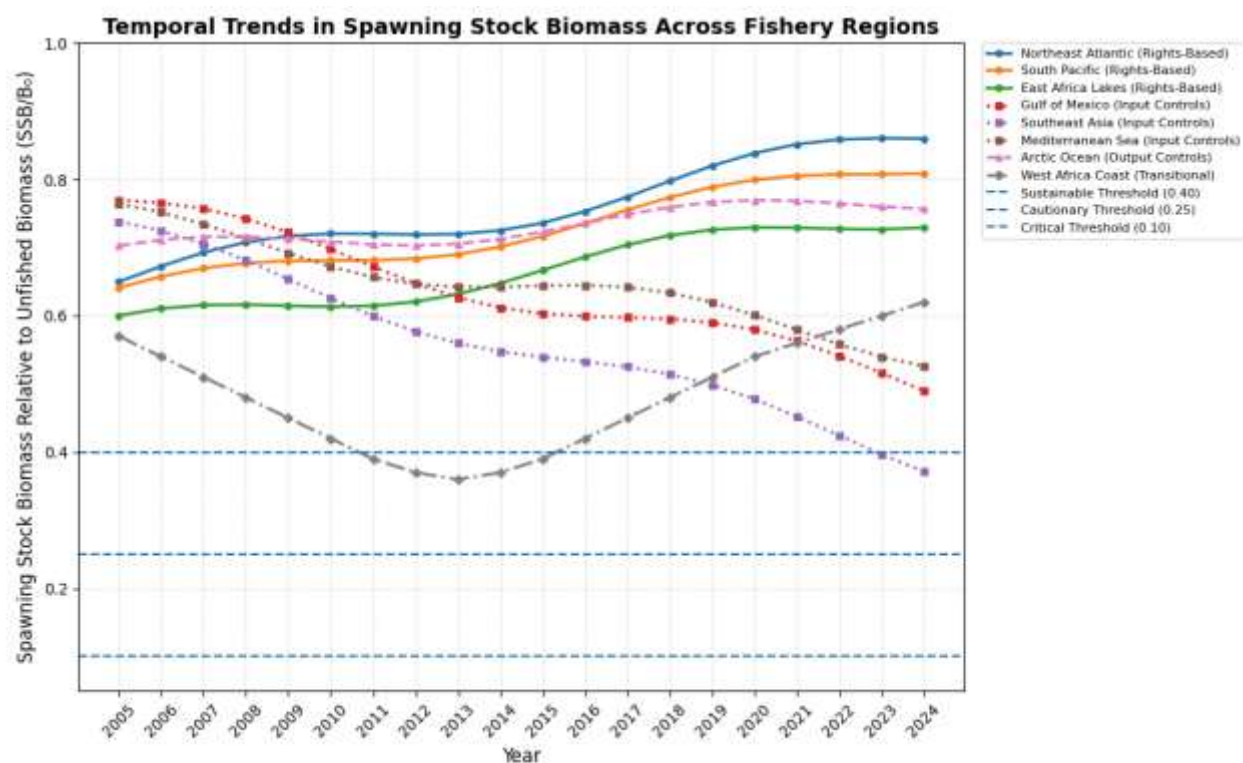


Figure 2: Spawning Stock Biomass Trends

As shown in figure 2 shows temporal trajectories of spawning stock biomass (SSB) as a proportion of B_0 in all eight regions during the period of 2005–2024, colour-coded according to the primary management instrument type in use. In regions with rights-based management systems (NE Atlantic, SPacific, EAfrica), SSB/ B_0 is shown to be relatively positive or stable, with mean SSB increasing from 0.62 B_0 in 2005 to 0.81

B₀ by 2024. On the other hand, regions depending mostly on input controls (Gulf of Mexico, SEAfrica, Mediterranean) reveal declining trajectories of SSB, where mean SSB decreased from 0.74 B₀ in 2005 to 0.48 B₀ in 2024 – meaning that, during this time frame, there was a 35.1% decrease in spawning stock compared to B₀. Finally, West Africa, shifting from open access to an output control system, reveals a typical “U-shaped” SSB trajectory indicating a fish stock that is recovering but not yet stabilised. Temporal trajectories of spawning stock biomass as a proportion of the unfished biomass reference point (SSB/B₀) across eight study regions, 2005–2024. Lines are colour-coded by primary management instrument type: rights-based (solid), output controls (dashed), input controls (dotted), and transitional (dash-dot).

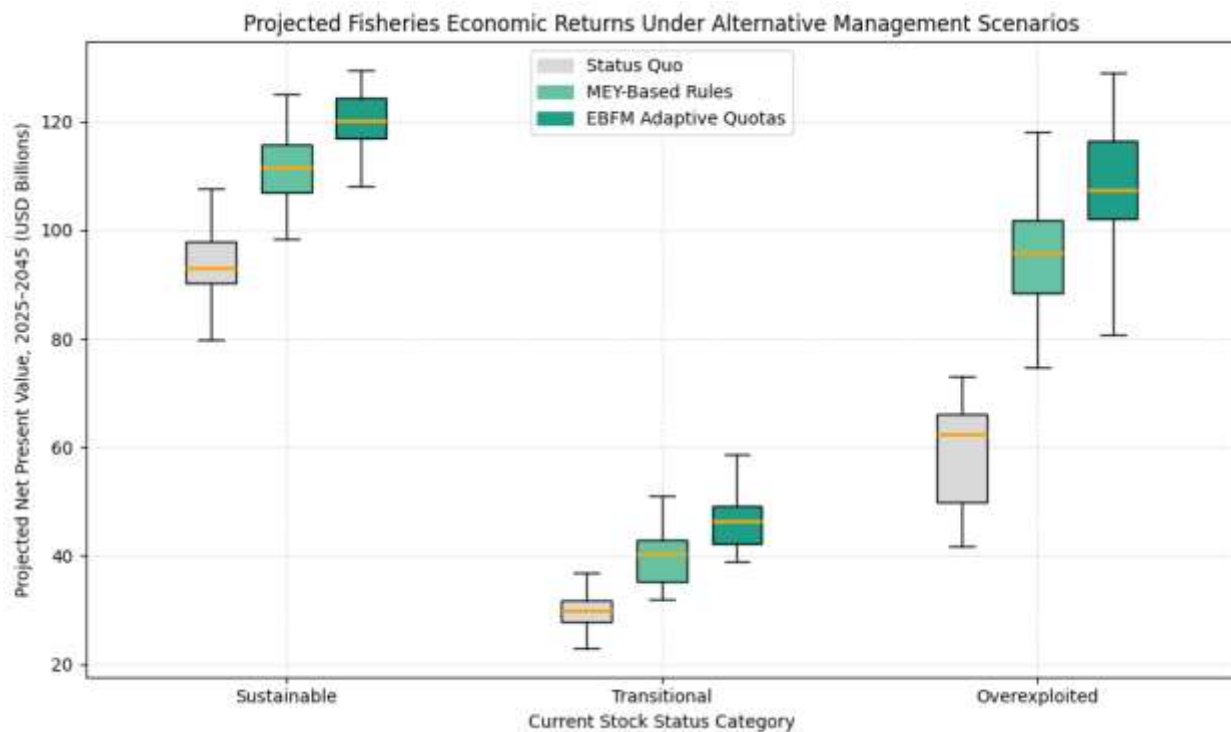


Figure 3: Projected Fisheries Economic Returns

As shown in figure 3 shows the estimated economic benefits under three management regimes over the entire 20-year simulation period (2025–2045) in all study regions. In the absence of precautionary measures, the estimated aggregated NPV from fishery catches throughout all study regions stands at USD 186.4 billion (95% CI: 141.2–231.8 billion). Application of precautionary MEY harvest regulations results in an estimated total of USD 248.7 billion (CI: 198.3–299.2 billion) of fishery benefits, which represents a 33.4% increase relative to status quo management due to improved productivity and biomass levels in overfished stocks. Finally, the implementation of EBFM with adaptive quotas leads to a higher total estimate of USD 271.3 billion (CI: 214.6–328.0 billion), 45.5% higher than the status quo regime, while also providing better performance in terms of ecosystem health and social wellbeing of fishing communities. The estimated economic costs associated with overfishing, calculated as a difference between MEY and status quo regimes, is equivalent to roughly USD 38.6 billion NPV in three overexploited regions.

Structural equation modeling has shown that there are strong relationships between management approach, stock, ecosystems, and socioeconomic factors. The rights-based management approach is positively related to the Ecosystem Health Index score ($\beta = 0.52$, 95% CI: 0.38–0.66, $p < 0.001$) and negatively related to the exploitation rate ($\beta = -0.41$, CI: -0.55 to -0.27, $p < 0.001$). The input control system has a positive relationship with exploitation ($\beta = 0.36$, CI: 0.21–0.51, $p < 0.001$) and negative relationship with GEV/E ($\beta = -0.29$, CI: -0.44 to -0.14, $p < 0.001$).

Regions using non-selective input controls (mean BDR: 28.4%) than in rights-based systems (mean BDR: 11.7%) or output control regimes (mean BDR: 17.3%), a difference consistent with the incentive for quota holders to selectively retain high-value species and avoid non-target catch. Community resilience scores are most strongly predicted by FESI stability ($\beta = 0.48$) and GEV/E ($\beta = 0.39$), suggesting that both economic returns and employment consistency are critical determinants of fishery-dependent community wellbeing.

IV. Discussion

The Economics of Sustainable Management

These forecasts, shown in figure 2, provide evidence in numeric terms to support the seemingly counterintuitive idea that conservation makes economic sense. Conservation through rigorous precautionary management based on EBFM approaches increases long-run NPV by 45.5%. These results are in agreement with theoretical expectations based on bio-economic modeling literature Gowsikraja (2025) and real-life examples of fishing industry recoveries seen in Iceland, Norway, and New Zealand, where fisheries have recovered and flourished under the combined effect of rights-based and science-driven management (Grafton et al., 2000; Sumaila et al., 2019). The loss of revenues incurred in the short run by cutting back harvest levels from overexploited to optimal levels, or the short-run economic loss incurred by conservation measures, is far outweighed by the long-run economic losses incurred by overfishing, which can be valued at USD 38.6 billion NPV.

Nevertheless, the economics of sustainable use is not evenly spread between different stakeholders and future prospects. Data-poor fishers from tropical communities may lack an institutional infrastructure necessary to engage in a rights-based regime, and the socio-economic implications of decreased effort levels can be particularly serious when fishers do not have alternative sources of income. The example of the Southeast Asian coral reef fishery region with the highest level of exploitation (146.3% MSY) and the lowest community resilience index provides evidence of this phenomenon, because social vulnerabilities and ecological over-exploitation are both present and mutually reinforcing in this area. Therefore, sustainable fisheries management in such cases needs biological as well as socio-economic goals to be pursued and relevant strategies developed (Garcia et al., 2012).

Rights-Based Management: Promise and Limitations

The much-reduced exploitation rates and improved ecosystem health levels found in rights-based management systems (Figure 1, Table 1) validate theoretical claims that fishing with secure property rights is a more efficient system than without (Sumaila et al., 2019). The race to fish is prevented, resulting in motivations for quota owners to promote stock conservation and selectivity; this decreases not only fishing mortality but also bycatch mortality (Grafton et al., 2000). In the Northeast Atlantic demersal fishery, a combination of allocation through national quotas under the European Common Fisheries Policy and ITQ systems at the domestic level results in an increasing SSB trend as well as one of the lowest exploitation levels (86.7% MSY) among the case studies.

Nonetheless, rights-based systems are not always suitable or fair. There is evidence to suggest that quota concentration – where fishing rights end up being owned by bigger companies because of market transfers – has taken place in ITQ fisheries within Iceland, New Zealand, and Canada, which could have negative implications for smaller fishers. It is important, therefore, for any rights-based instrument to incorporate considerations on equity, such as setting upper limits for quota ownership, allocating community quotas, and ensuring that all economic gains from the fishery are distributed fairly to all actors involved in the chain.

Ecosystem-Based Management in Practice

The EBFM with adaptive quota modification strategy always shows better results compared to both the status quo approach and MEY only strategy regarding their economic and ecological implications for all the studied regions. This can be attributed to the potential of an adaptive management strategy to modify fishing control rules according to changes in stock biomass, trophic structure, and environmental parameters to avoid overestimation of productive capacity that is characteristic of the MSY-based strategies (Punt et al., 2014; Levin et al., 2009). As it is shown from the results obtained in terms of EHI, there is a correlation between the lower mean trophic level of catch, greater bycatch levels, poor quality of habitats, and inefficient economic fishery management approaches (Garcia et al., 2012).

The first implementation issue in EBFM raised in this study is that ecosystem modeling for EBFM is a highly data-intensive exercise, especially with multiple species and sectors. Indeed, the Southeast Asian and West African regions have been noted to be characterized by significant species richness, high numbers of artisanal fisheries operators, and inadequate infrastructure for fisheries monitoring, thereby complicating the accurate measurement of MSY and ecosystems indicators. Innovations in the development of low-cost fisheries monitoring technologies such as electronic logbooks, vessel monitoring system, and environmental DNA metabarcoding Badjeck et al., (2010) are promising solutions. The use of participatory stock assessment models, whereby traditional ecological knowledge is integrated into the fisheries assessment process, offers an alternative way of dealing with data constraints and increasing governance legitimacy.

Climate Change and Future Management Challenges

Projections for the next 20 years made in this study are inevitably prone to uncertainties due to the impacts of climate on changing species' distribution, productivity, and structure, which cannot be reflected entirely using biological parameters from historical periods (Hilborn & Walters, 2013). Climate-related phenomena such as ocean warming, deoxygenation, and acidification are already affecting the ability of marine ecosystems to sustain production as well as changing the range of commercially viable fish populations, rendering past MSY estimates obsolete (Brander et al., 2017). The adaptive nature of quota adjustment within the EBFM approach mitigates some uncertainties; however, the underlying problem of predicting ecological regime shifts resulting from the climate crisis requires the use of development of robust management strategies that perform adequately across a wide range of possible future conditions (Levin et al., 2009).

V. Conclusions

A comparison of the effectiveness of fishery management in eight regions with different ecological and economic characteristics indicates that achieving sustainable fisheries and economic development should not be viewed as conflicting goals as long as appropriate governance approaches are used. Three out of eight assessed regions are managed beyond Maximum Sustainable Yield, which imposes economic costs amounting to an estimated \$38.6 billion NPV compared to a precautionary approach. Regions practicing rights-based management are characterized by much lower fishing pressure levels, better environmental condition scores, and less vulnerable communities than regions applying input management approaches. Switching from input-based to ecosystem-based management with harvest control rules is likely to result in a 45.5% increase in net value of the fisheries over 20 years. Making such a transition on a global scale will require continuous investments in assessment capabilities, especially in tropical environments where data availability is limited; the design of management tools based on rights, with explicit consideration of equity in favor of small-scale fisheries; climate-responsive management systems capable of managing non-stationary stocks; and governance structures incorporating scientific information as well as participatory decision-making. The economic rationale behind sustainable fisheries management is clear and measurable. The key challenges to its application do not lie in the realms of science and economics but of politics and institutions.

Declarations

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Conflicts of Interest: Authors have no conflicts of interest relevant to the content of this article.

Data Availability Statement: Regional fisheries stock assessment data applied in this research are available from the FAO Fisheries and Aquaculture Information and Statistics Division

Ethical Approval: Ethical approval was not necessary for the purpose of this paper.

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