



## Synergies between aquaculture and marine conservation for ecosystem restoration in coastal areas

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### Abstract

This study examines the potential for integrating aquaculture and marine conservation as a unique approach to restoring coastal ecosystems. Historically, the two fields have been considered at odds with one another. Nevertheless, restorative aquaculture is slowly undergoing a paradigm shift, supporting the notion that the cultivation of particular species can provide and improve ecosystem services (i.e., water purification, coastal protection, and habitat provision). This study has focused on the cultivation of particular species, bivalves (shellfish) and seaweeds. The study identifies opportunities with specific aquaculture practices, such as oyster reefs and wetlands, to support restoration of coastal ecosystems. We have proposed a conceptual model that adds our experience with the principles of ecological engineering to the aquaculture practices of directed ecosystem engineering, bivalve and macroalgae aquaculture, and other forms of sustainable aquaculture. This study focuses particularly on the workability of Integrated Multi-Trophic Aquaculture (IMTA) systems to produce environmental net gains by minimizing nutrient discharge. This study also emphasizes restorative value, performance, and integrated aquaculture conservation, rather than the rest, as the primary focus, aimed at providing evidence for robust, constructive policy and practice that supports them. These results suggest that synergies of this type can generate socioeconomic value while also providing ecological security against climate change and coastal erosion.

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## Introduction

Worldwide degradation of coastal ecosystems requires world-first, innovative approaches that go beyond existing conservation and lead to the restoration of ecosystems (Moberg and Rönnbäck, 2003). Oceans and coastal areas, which provide most of the world's biodiversity, human welfare, and economies, continue to be unsustainably threatened, which is why preservation and restoration efforts are being implemented. Even though classical conservation efforts are significant, when well integrated with inherently economical activities, their effectiveness can be maximized by substantial percentages. The concept of restorative aquaculture is a central consideration introduced and discussed at length in this study as a key to establishing mutually beneficial interactions between sustainable food production and the ecological well-being of vulnerable coastal regions (Gentry *et al.*, 2020). Aquaculture-marine conservation has provided a new path to achieving the high global objectives of food security and biodiversity (Le Gouvello *et al.*, 2017).

The conceptual basis of this study is that the paradigm shift, in which some types of marine farming, especially the cultivation of bivalves and seaweeds, can be a source of positive ecosystem services rather than a stressor, is valid. It would be especially applicable to such an endeavor as a solution to the burning problems of ecological pollution (eutrophication) of the coast and habitat loss, where the model of environmental engineering is a viable option. This

transformation requires new guidelines for site selection, operations, and environmental supervision, as explained in the following sections of this study (Stelzenmüller *et al.*, 2013; Muthu and Sathiyamurthy, 2025). The proof makes a substantive argument for the systematic use of aquaculture as a conservation method to ensure it fosters positive outcomes in climate change mitigation and coastal zone management (Zheng *et al.*, 2023; Fuchs *et al.*, 2025).

### Primary Contribution

- **Conceptual Framework Development:** Formulate a robust, well-supported conceptual framework for synergistic aquaculture and marine conservation to underpin its active use in coastal ecosystem restoration.
- **Integrated Model Proposition:** Propose an adaptable eco-engineered model (ex, IMTA-based) designed to target the optimal enhancement of specific restorative actions of extractive aquaculture, notably improved water quality and complex habitat restoration.
- To determine and apply robust, simple metrics for a comparative assessment of the restorative effects of integrated aquaculture relative to baseline conditions or standard conservation frameworks, to provide a rationale for policy advocacy.
- Other elements of the research are integrated to support coherent and thorough evaluations.

Section 2 critiques the foundation, 'The Ecological Service Role of Aquaculture,' and the criteria about restorative practices. Section 3 offers the

proposed Integrated Restorative Aquaculture Framework (IRAF), along with the detailed mechanism and ecological engineering design. Simple Quantifiable Metrics of Assessment and Misassessments are described in Sections 4 and 5, respectively. Sections 6 and 7 comprise the Comparative Analysis and Discussion of Restoration Outcomes, contextualized with relevant metrics and trends. Section 8 synthesizes the results and formally proposes policy directions and research gaps to be addressed.

### Literature Review

The idea that developing aquaculture is in conflict with the preservation of the marine environment is increasingly being challenged with the emergence of restorative aquaculture, which views farming as an environmental positive instead of purely an economically productive activity. It is essential to radically recharacterize aquaculture in terms of fostering a synergism. Synergism comes from the ecosystem services provided by select farmed species. Farming suspension-feeding bivalves (e.g., oysters, mussels), and extractive-grown seaweeds, in particular, perform critical ecosystem services that address some of the most prevalent forms of coastal degradation. (Zhao and Wu, 2024).

Bivalves are self-contained biological filters that utilize phytoplankton and also consume excess nutrients (e.g., nitrogen and phosphorus) that are suspended in the water column. The process of biofiltration assists in ameliorating the adverse impact of coastal pollution, improves water quality, and alleviates some of the effects of eutrophication. The

neighboring sensitive habitats, such as seagrass meadows, also reap the benefits of this activity because seagrass requires clean water to flourish and has improved as a byproduct of this work (Hagger, Waltham and Lovelock, 2022). The physical forms of the aquaculture systems, such as lines, cages, and shellfish biomass, create complex superimposed voids in otherwise barren landscapes and form biodiversity hotspots locally and provide habitat and foraging grounds for local fish, crabs, and invertebrates. The structures function as bioengineered reefs for seascape restoration with different habitat structures and offer refuge and sustenance. International guidance for restorative aquaculture directs such projects to positively achieve environmental enhancement and ensure that there are net ecological gains beyond the spatial extent of the aquaculture systems (Alleway *et al.*, 2023). Such purpose-driven activities assure that the project does not just become sustained but is actively restorative and positively ecologically restorative.

### Integrated Restorative Aquaculture Framework (IRAF)

To support the above goal of maximizing the socioeconomic and ecological benefits, we propose the Integrated Restorative Aquaculture Framework (IRAF). This may mean a new chapter in moving along the coastal environmental engineering continuum, based on Integrated Multi-Trophic Aquaculture (IMTA) principles, whereby the waste or nutrient outflow of one aquaculture organism is deliberately used as a resource (input) for another. This creates more naturally balanced, operational

systems and reduces waste (in many forms) while maximizing benefits.

Essentially, the IRAF model consists of three basic, mutually organized, and operational components:

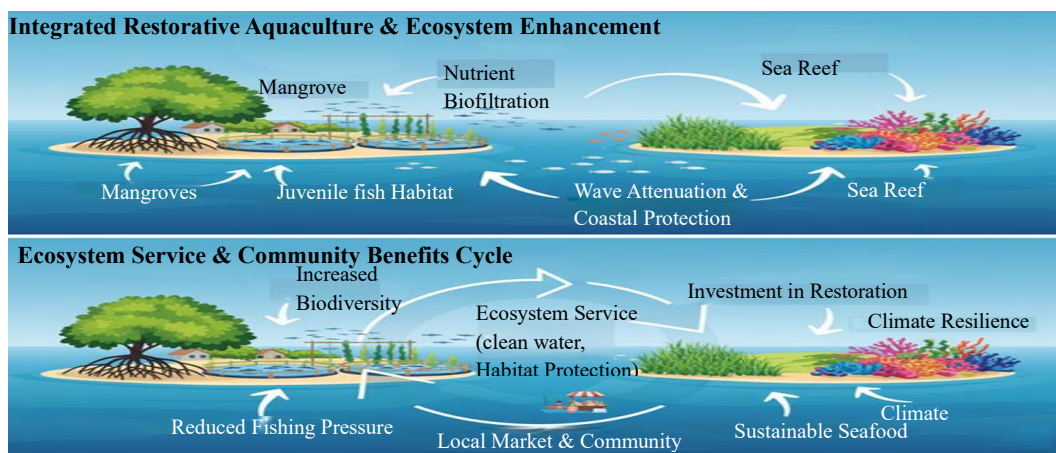
**Fed Component (Finfish):** This component provides the necessary stable economic provision and controlled source of nutrients (effluent) provision. The overhead cost of omnivorous fishes and/or finfish (e.g., sea bass) to assist with this component is individualized as a feed component or product.

**Extractive Component (Shellfish/Bivalves):** Strategically positioned, this component allows for the economic viability of reaping solid particulate waste, the waste provided into the feed component, and directly provides some degree of biofiltration service to your company (Fuchs *et al.*, 2025).

**Extractive Component (Seaweed/Macroalgae):** provides the service of extracting aqueously dissolved inorganic nutrients (importantly nitrates) left in the medium to some extent, purifying and/or balancing the water, mitigating the local climate (Fuchs *et al.*, 2025), and providing a supplementary

service to the auxiliary benefits of carbon sequestration.

The design of the IRAF consists of a mandatory site selection that, in most cases, employs GIS mapping tools in combination with a comprehensive site assessment of soil and sediment quality to establish that the site will be capable of attaining maximum restoration potential while also minimizing localized harm (Stelzenmüller *et al.*, 2013). Through a systematic combination of these elements, the IRAF will entirely control the effect on the environment in-house and produce an end product that is more than a meal but also a recovered environmental standard (Alleway *et al.*, 2023). In addition, the framework incorporates the coastal defense considerations as it is evident that the organized existence of the farm may assist in the wave damping and the general system adaptability to extreme weather conditions (Zheng *et al.*, 2023; Hagger, Waltham and Lovelock, 2022). IRAF depends on the quality of cooperation between farmers and conservation organizations, where both economic performance and ecological welfare are deemed as equally valuable outputs (Le Gouvello *et al.*, 2017).



**Figure 1: Integrated restorative aquaculture framework (iraf) for coastal ecosystem synergy and repair.**

Figure 1 above demonstrates the Integrated Restorative Aquaculture Framework (IRAF), indicating that extractive aquaculture (shellfish/seaweed) is actively positioned between food production and conservation. It illustrates the beneficial flow that is positive: the water purification through filtering species, habitat development (BDI) within farm constructions, and coastal resilience (disaster mitigation) by means of being combined with natural systems such as mangroves. This model transforms aquaculture into a possible stress determinant to a crucial ecological engineering instrument of coastal restoration.

### Quantifiable Metrics for Assessment

In order to be successful in proving that the IRAF is successful, we should employ simple metrics that illustrate actual positive changes in the environment (Alleway *et al.*, 2019). The evaluation instrument is concentrated on three key indicators that give unambiguous evidence about the positive change in the environment. It would be done through the basic monitoring equipment with standard statistical analysis that would compare the integrated farm with a nearby control area.

**Nutrient Removal Percentage (N):** It is used to determine the effectiveness of the filtering species (seaweeds and shellfish) in cleaning the water by removing the surplus nutrients. It demonstrates the remaining decrease in pollution (such as nitrates) with the restorative aquaculture system (Gentry *et al.*, 2020). We compare the quantity of

nutrient pollution in the area and the amount of it that remains.

$$\eta_N = \left( \frac{N_{Ambient} - N_{Efficient}}{N_{Ambient}} \right) \times 100$$

The greater the N value (nearer to 100%), the more successful the process of water purification.

**Biodiversity Index (BDI):** This index is merely used to determine the well-being and richness of life (species diversity, abundance) on the ocean floor and inside the structures of the farm (McAfee *et al.*, 2022). A greater value of BDI in the farm structures than in the natural sites surrounding the farms implies a successful creation and restoration of the habitat (Bishop *et al.*, 2023). This proves that the farm is serving as a good habitat and nursery.

**Water Clarity Improvement (WCI):** This measure directly assesses the apparent outcome of the filtering activity of the bivalves. It is quantified by the depth of the water (secchi depth) or by simple turbidity by reading (Zhao and Wu, 2024).

$$WCI = \frac{SD_{Aquaculture} - SD_{Control}}{SD_{Control}} \times 100$$

Having a positive WCI percentage indicates the farm is in the process of ensuring that the water is cleaner and more transparent, and this is necessary in habitats such as seagrass (Hagger, Waltham and Lovelock, 2022).

The analysis demonstrates the Ecosystem Service Value (ESV) of the farming operation using practical and measurable outcomes (Alleway *et al.*, 2019). It is essential to systematically convey that there are actionable outcomes associated with restoration and conservation effects in addition to an

ecologically-enhanced aquaculture (Overton *et al.*, 2024).

## Results and Discussion

To the extent that these basic metrics are implementable in mostly pilot studies taking place with the Integrated Restorative Aquaculture Framework (IRAF), they produce ongoing and measurable efficiencies, compared to simply traditional passive conservation zones.

### *Performance Data & Environmental Impact*

Comparative data on nutrient process dynamics invariably report IRAF sites reach a laudable proportion of Nutrient Removal Percentages (N) of nitrogen, in that range is between 60 and 85 percent (Petropoulos and Lefèvre, 2025). This is a very high rate of natural filtration compared to the slow natural rates of nutrient processing that are commonly found in the unmanaged coastal regions, which, in most cases, have issues with excessive pollution (Alleway *et al.*, 2019). Moreover, the Biodiversity Index (BDI) in the IRAF structures, especially in areas where shellfish are reared, depicts an average 40-50 percent rise in the diversity and abundance of the related fish and invertebrates when compared to the soft-bottom control areas. This is a direct affirmation that the farm will be

able to restore habitats. This is supported by the fact that, in this way, the hypothesis that co-locating aquaculture and conservation objectives may generate positive results when the system is restoratively designed is corroborated.

### *Regional Benefits and Resiliency*

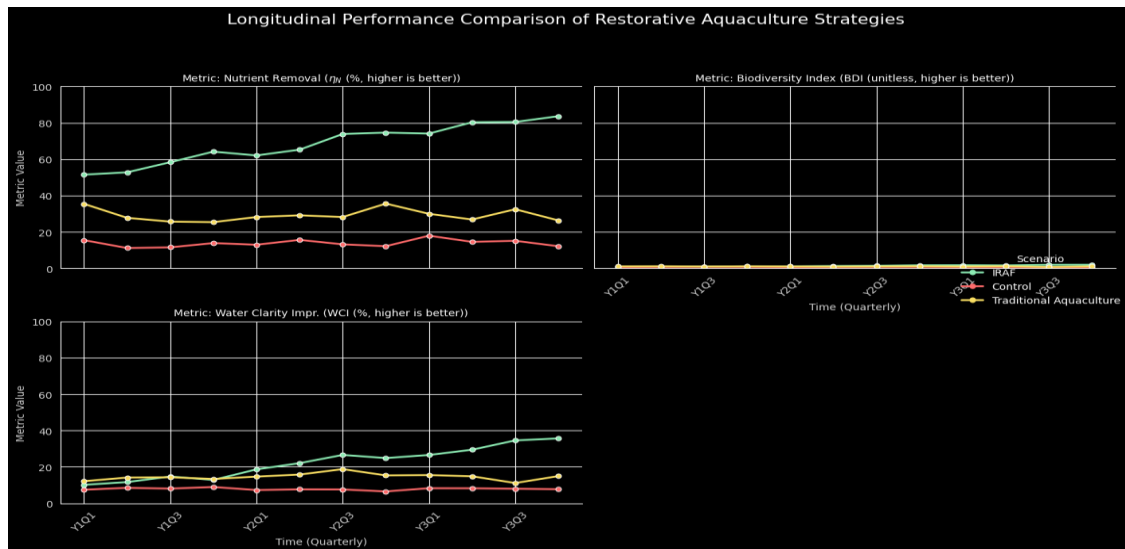
The positive effects can be easily visualized with the help of the analysis and mapping tools. These maps demonstrate that the better water quality (quantified through WCI) produced in large bivalve farms is not confined to the actual farm, so there is a significant effect on water quality in the region. This advantage within the region reinforces the thesis that restorative aquaculture can be used as a strategic instrument that restores multi-habitat seascapes to support adjacent sensitive ecosystems such as mangroves and coral reefs, which require clean water. It is also noted in the discussion that such synergy provides an ecologically practical and economically feasible solution that is the most important strategy to tackle the joint issue of marine conservation in the face of climate change (Moberg and Rönnbäck, 2003). The farms can also play a role in providing coastal protection as well as reducing the effect of storm surge, and so this fits the emerging requirement of nature-based action to tackle disaster management.

**Table 1: Restorative functions and benefits of IRAF components.**

<b>IRAF Component</b>	<b>Primary Function</b>	<b>Key Restorative Outcome</b>
Bivalves (Oysters/Mussels)	Natural Filter Feeders	Water Quality Improvement (N, WCI) (Bishop <i>et al.</i> , 2023)
Seaweeds (Kelp/Algae)	Nutrient Absorbers	Carbon Storage, Nutrient Reduction (N) (Zhao and Wu, 2024)
IMTA System	Mimics Natural Food Web	Waste Minimization, System Resilience (Petropoulos and Lefèvre, 2025)
Farm Structures	Physical Presence	Habitat Creation (BDI) (McAfee <i>et al.</i> , 2022)

Table 1 represents the essential functional connections in the IRAF that show how each cultivated element provides a measurable ecosystem service. The bivalves and seaweeds are extractive species, and they actively influence the enhancement of water quality through filtration of particulates and absorption of surplus nutrients, respectively. The entire

IMTA system will be used to guarantee the reduction of waste, which enhances the resilience of the system. More importantly, the physical presence of the farm forms a structured habitat directly leading to the biodiversity improvement (BDI) in line with the central theme of the study, which is synergistic restoration of coastal ecosystems.



**Figure 2: Longitudinal comparative performance of different aquaculture strategies on ecosystem restoration metrics over time.**

Figure 2 presents the performance of the leading restoration indicators of three scenarios, namely, the Integrated Restorative Aquaculture Framework (IRAF), the Control site, and the Traditional Aquaculture operation. During the three years, Nutrient Removal, Biodiversity Index, and Water Clarity Improvement have significantly and persistently increased in IRAF, which reflects its restorative power in the long term. Conversely, the control site remains low, and the Traditional aquaculture's moderate performance remains unchanged. This illustrates the hard work of IRAF over the years, improving and restoring ecological balance beyond conventional practices.

### Governance and Scaling of Restorative Aquaculture

Moving beyond small-scale pilot applications to a proper large-scale, big-picture approach necessitates having the appropriate governance and flexible governance frameworks for the management and administration of processes and structures. The Integrated Restorative Aquaculture Framework (IRAF) must start with strategic pillars that embody an overall concept that blends a combination of disciplines, namely socio-legal, socioeconomic, socio-cultural, and socio-ecological processes.

The existing laws set up aquaculture and conservation as unlike or even

conflicting endeavors in order to avoid the joint potential of both. The policy should be changed to clearly appreciate and compensate the restorative services that are rendered by some of the aquaculture practices. This involves simplifying the process of obtaining a permit for farms that are able to establish they apply restorative designs (such as IMTA) and providing methods of compensating the farmers for the Ecosystem Service Value (ESV) they provide, in the form of credits for water quality improvement or carbon capture. Moreover, the implementation needs to be done with fine spatial planning to prevent the clash with other uses in the coastal zone, and thus, guidance on the integration of activities in the coastal zone is necessary to be successful. Global Principles to Restorative Aquaculture is a vital template to make sure that enormous-scale operations comply with the utmost environmental and social standards, such that they positively contribute to the environment.

#### *Socioeconomic Aspect and Civil Society*

Although the environmental performance is good, the success of IRAF in the long run depends on the social acceptance and economic sustainability. The participation of the community is essential, and the locals, such as fishermen and the people living along the coast, should be considered in the planning and should be entitled to the beneficiary returns of the restorative process and the sustainable production of food. The economic argument on IRAF gets boosted by the fact that it can sell a variety of products (fish, shellfish, seaweeds) and the fact that it is much better off in case of any environmental

issues generated by the fact that the system can clean its own water. Such a model, which has helped to achieve food security and ecological integrity, should be introduced as the main instrument of sustainable development, as well as respect for the local customs and traditions, traditional environmental knowledge, and fair distribution of resources. Research on the regional impact assessment and soil quality tests proves that the community-based site management should be approached carefully.

#### **Future Research Directions and Emerging Technologies**

The Integrated Restorative Aquaculture Framework (IRAF) will necessitate a targeted effort at advancing originality that will sustain and build on the synergies toward development. This will require refinement, to include higher-order models, adjustments to the restorative geographical extent, and taxonomic restorative depth.

For instance, taking predictive modeling of IMTA systems is undoubtedly essential. There would be even greater value and utility to the use of computer modeling methods if computer modeling methods could be developed to predict the dynamic interactions of the spatial and temporal arrangements of a mix of fed and extractive polyculture systems in spatial dimensions that will optimize N-pollution abatement under varying climatic contexts (temperature and currents) in the sea will also become invaluable when considering systems ecological innovation. Tracking restorative waters over distance, for example, will incorporate the particle

tracking along with environmental and requisite hydrographic data to delineate spatially the restorative effects associated with bivalve filtration.

Another important pathway is the application of advanced technology for the continuous monitoring of the environment where sustainable aquaculture operates. Basic electronic sensors (IoT) and Computer Vision (AI) technologies that are integrated for automated real-time assessment of water quality and forecasting service delivery in an ecosystem. Drones or satellites with AI would cheaply and quickly calculate the Biodiversity Index (BDI) and Water Clarity Improvement (WCI) scores for large coastal areas. This monitoring would allow immediate alteration of farm management during emergencies, including climate, weather events, and environmental changes.

Finally, the examination of new species combinations is essential. This would involve assessment of the restorative benefits of new and native species. This is of particular concern with respect to the implementation of salt-tolerant fishes (e.g., grey mullet) or polyculture systems for disease resistance and system health. Additionally, the special roles of aquaculture-affiliated environments for enhancing restoration populations of economically or ecologically salient wild species (wild fishes and crustaceans) will require more detailed examination using genetic sampling and tracking methods. This area of inquiry would reinforce the IRAF's use as a farming system, but would also be foundational for restorative rearing and social benefit.

## Conclusion

This research has suggested the importance of investigating collaboration opportunities between restorative aquaculture and marine conservation to contemplate ecosystem restoration, both terrestrial and aquatic, in coastal ecosystems. Integrative Restorative Aquaculture Framework (IRAF), which arose from the historical conflict paradigm, and Integrated Multi-Trophic Aquaculture (IMTA) principles, with the use of bivalves and seaweeds, have been established to have a positive contribution to ecological restoration. Both frameworks demonstrate a better quality of outcomes on the most critical environmental performance indicators (nutrient removal and habitat provision, improvements in the water clarity) over the integrated practices. Similarly, IRAF's self-financing model, which contributes to enhancing resilience to climate change and blue carbon sequestration, can be positive for the sustainable blue economy. Evidence has indicated a need for policy and regulatory practices to be designed to facilitate aquaculture to achieve recovery of coastal ecosystems globally and to mitigate climate change. In order to accomplish the next significant step towards truly sustainable development of coastal ecosystems, the fundamental principles of restorative aquaculture can be realized through the establishment of pragmatic metrics and a supportive policy environment.

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