INTEGRATED MULTI-TROPHIC AQUACULTURE Perspectives for More Sustainable Seafood Aquaculture

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INTEGRATED MULTI-TROPHIC AQUACULTURE

Perspectives for More Sustainable Seafood

Aquaculture: The need to meet seafood demand

Seafood is recognized as an essential source of nutrients for humans and is appreciated as a festive meal around the world. The annual growth in its consumption – an average of 3.1% per year from 1961-2017 (FAO, 2020) – is the highest of all food products due to the increase in individual consumption and to population growth. In parallel, fishery catches have plateaued for several decades, due to a decrease in multiple fish stocks, and thus cannot meet this growing demand.

Therefore, aquaculture seems the only alternative to address the growth in seafood consumption. Aquaculture encompasses a large number of species and practices. As observed in other agricultural sectors, intensification of aquaculture production has multiple disadvantages from environmental and social perspectives. In particular, fish farming increasingly depends on the use of external inputs (e.g. ingredients such as fish meal and oil, energy sources) and is accused of impacting natural ecosystems. Practices must change to address this quantitative issue in a sustainable way.

Aquatic ecosystems: Models for aquaculture development

Aquatic environments contain a large diversity of species whose differing roles in nutrient and energy cycles contribute to the balance of ecosystems. Species of plants (algae, macrophytes, phytoplankton), invertebrates (insects, crustaceans, mollusks, zooplankton), vertebrates (amphibians, fish), and microorganisms interact in complex trophic webs and exploit the resources available in aquatic ecosystems. They also live in different biotopes, which use space in aquatic ecosystems in a complementary manner. These interactions regulate the natural productivity of ecosystems.

The agroecology movement in the agricultural sector is based on using ecological functions to produce food better, use fewer agrochemical inputs, and decrease environmental impacts. Aquaculture can also tend toward "ecological intensification" by using ecological functions of aquatic ecosystems, especially the diversity of aquatic species. Integrated Multi-Trophic Aquaculture (IMTA), by associating different complementary species, such as fish, filter feeders, detritivores, and primary producers, provides new pathways for aquaculture development.

TOPIC 1 Perspectives for More Sustainable Seafood

Principles and history of fish polyculture

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Aquaculture has developed greatly in the last century, but the origin of the farming of fish and other aquatic organisms goes back long before modern history, sometimes being lost in myths. Polyculture, one of the most ancient practices, has now returned to aquaculture.

Farming multiple species in the same pond was practiced as early as the 7th-9th centuries in both Asia and Europe and was based on recreating a natural ecosystem with a certain degree of control over the nutritional niche of each species. Ponds were already part of networks of agroecological flows in the 16th century, when fish were fed cereals, and pond sediments were used to fertilize arable land. The "traditional ecological knowledge" enriched over generations is still applied in carp and shellfish culture. This knowledge is becoming the core of modern scientific arguments, such as the ecosystem approach to aquaculture, carrying capacity, ecosystem services, and IMTA, all of which influence the current social acceptance of aquaculture.

Ecosystem services of pond systems

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Aquaculture can provide several services to humans besides producing food. The ecosystem services concept was developed to capture all services provided by natural ecosystems: provisioning, regulating, and cultural services, all of which are sustained by support functions. Pond systems, on the border between natural and managed ecosystems, are known to provide a wide range of services. The variety of support functions, such as supporting biodiversity or maintaining water and nutrient cycles, regulates the climate, hydrology, aquatic pollutants, and diseases. Pond systems also provide several cultural services, since they are appreciated for their role in structuring landscapes, are enjoyed by tourists, and host specific and remarkable species (e.g. birds, amphibians, invertebrates) that can be observed by visitors or become the focus of hunting and angling activities. They also help educate people about the natural world. Nonetheless, provisioning services, such as the provision of fish, other human-consumed species (e.g. invertebrates, plants), and sediments for fertilizer, are the main targets, which drive management practices and maintain the richness of these systems.

The strategy of separating of fed/non-fed areas: Principles and advantages

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Farming several fish species in polyculture ponds is an age-old method that produces more fish in a sustainable manner. It benefits from an ecosystem's carrying capacity and nutrient recycling when the main farmed species is fed and additional species are reared on the natural food that feeds on residual nutrients. IMTA practices include separation enclosures in ponds.

To improve the overall efficiency of the production system, farmers must manage the biomass and feed conversion rate of fed species, which requires increasing the stocking rate and allowing the additional species to recycle the residual nutrients directly (filter feeders) or indirectly (macroalgae feeders).

Several advantages of separation enclosures are observed. They permit an easier monitoring of health, growth, and feeding. They are easy to install, and permit an easy management in emergency, a better predation control, and a simpler application of treatments. The supplementary feeding practices oriented towards the target species induce an increase in feed efficiency. The use of separation enclosures simplifies harvesting at any time in the year.

TOPIC 2 Interactions between Fish and Plants

Coproduction of macrophytes and fish: the case of *Azolla*-Gourami in Indonesia

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Floating macrophytes and fish biodiversity may represent a major asset for the ecological intensification of aquaculture. Five macrophytes that are widespread in Indonesia were studied to identify those most suitable for aquaculture production, based on six relevant parameters. *Azolla* filiculoides and *Lemna* spp. were the most suitable, and *Azolla* was studied further.

Giant gourami can eat large amounts of fresh Azolla, and replacing a certain percentage of commercial fish feed with Azolla increases their resistance to disease and stress. However, decrease in fish growth is observed if more than 30% of the feed is replaced, which is not sustainable.

Azolla coproduction was discontinuous due to the trapping of nutrients by sediments of the earthen ponds and to grazing by invertebrates. However, 15% of fish feed was saved with no negative impact on gourami growth and survival.

Fish farmers perceived ecological intensification positively and were greatly interested in this macrophyte-fish association, but implementing it was challenging. Nonetheless, they adapted the original technique to their own production system, which provided more resilience and sustainability to their farms.

Interaction of fish and *Ulva* spp. in recirculating systems: Improvement of fish welfare

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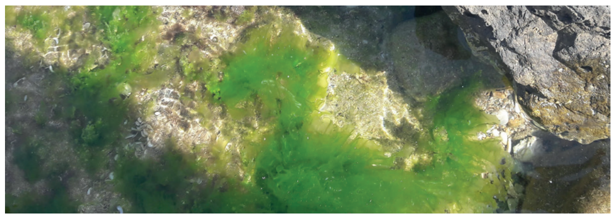
To examine the interaction between fish and *Ulva* spp., European sea bass were reared in indoor recirculating systems (RAS) with or without Ulva spp. (*Ulva*-RAS and control-RAS, respectively).

When 55% of dietary fish oil was replaced with a mixture of rapeseed oil and palm oil, the growth of sea bass in *Ulva*-RAS was isometric, with an increase in the condition factor and protein, lipid, phosphorus, EPA and DHA contents compared to those in control-RAS, which had increased weight variance.

When sea bass were fed a diet with fish oil derived from unavoidable unwanted sardines, growth performances were similar in both RAS. When the fish were subjected to a hypoxia test, however, those in *Ulva*-RAS lasted nearly twice as long before becoming immobile, and had blood parameters that indicated better physiological status, than those in control-RAS.

Ulva spp. in RAS was beneficial for sea bass, since it improved the response to nutritional stress caused by replacing fish oil with vegetable oils and to hypoxia stress, thus indicating that *Ulva* spp. in IMTA can improve fish welfare.



Rice-fish culture: the paragon of agroecology?

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Rice-fish culture is a model of integrated agroecological practices that has developed in tropical areas. It uses raised dikes to increase the water level in irrigated paddy fields and provides refuge channels to protect fish from heat and predators.

Fish behavior and excretion (fertilization) increase paddy rice production by 20-30%, which compensates for the cultivated area lost to the refuge channels. Paddy fields provide a habitat and nursery for fish, and they support biodiversity. Fish benefit from natural biodiversity and improve pest management (e.g. weeds, insects) which decreases the need for chemical treatments. Rice-fish culture produces both fish and paddy with water supply saving (dual use).

Increasing the efficiency of this agrarian-aquatic ecosystem by improving knowledge about trophic dynamics would promote its agroecological intensification.

TOPIC 3 Water Purification

Producing phytoplankton from dissolved fish waste

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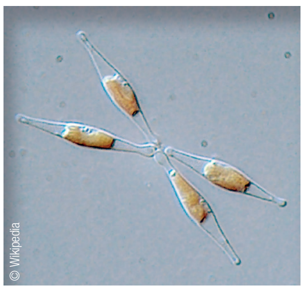
By associating species with complementary diets, IMTA reproduces a simplified trophic chain in which primary producers, such as macroalgae and phytoplankton, play a key role. Through photosynthesis, phytoplankton captures CO_2 and provides O_2. Phytoplankton also use nutrients (nitrogen and phosphorus) to grow and provides valuable biomass (e.g. new feed ingredients, green energy).

We demonstrated the ability of land-based IMTA to produce phytoplankton which purify water that contained dissolved waste from fish. Microalgae in RAS-IMTA systems have good potential for nutrient remediation. Adding silicate shifted the dominant microalgae species to diatoms such as *Phaeodactylum tricornutum* and *Cylindotheca closterium*, which have characteristics that may be useful for feeding oyster cultures.

Phaedactylum tricornutum



Hediste diversicolor

Role of filter feeders: Lessons from oysters

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Phytoplankton can serve as food for high-added-value species, such as oysters. Juvenile oysters assimilated specific diatoms, which changed their isotopic signature towards a microalgae signature. After the distribution of algae was optimized, IMTA oysters doubled their growth during the experimental period, showing the ability of land-based IMTA to associate fish, microalgae, and oysters successfully.

Recycling suspended solids: The worm way

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Aquaculture can release large amounts of organic matter in the form of feces and uneaten feed. Detritivorous species can consume organic particulate matter, which reduces benthic eutrophication and potentially the environmental footprint of aquaculture. We explored the bioremediation potential of detritivorous species. The ragworm (*Hediste diversicolor*) is a promising species due to its broad feeding behavior and its resistance in a wide range of environments. We studied the amount of organic fish waste that a ragworm can eat. A 98-day growth experiment was conducted with two types of food (fish feces and fish feed), and its results were used to calibrate a bioenergy model that estimated the bioremediation potential of ragworms. We estimated that a 100 m^2 ragworm farm (with a density of 3700 individuals per m^2) could assimilate 75-289 kg of fish waste per year, which is equivalent to a 2-9% reduction in the waste produced by a 20T seabass farm.

The paradox of planted lagoons in ponds

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Developing aquaculture systems that are both productive and environmentally friendly is an issue for sustainable production in the future. Associating aquatic species from different levels of a food web can increase the efficiency of nutrient and energy use. We associated a planted lagoon with a fishpond (polyculture of common carp, roach, and perch), in which water circulated in a closed loop from one compartment to the other. This system improved water quality (decrease in nitrogen, phosphorus, and blue algae concentrations in the water) and increase biodiversity. However, it decreased fish production by 15% and phytoplankton concentration by 83% compared to a similar fishpond without a planted lagoon. Thus, increasing biodiversity increases competition for the use of nutrients, which increases the overall production of biomass and decreases emissions into the surrounding environment, but at the expense of fish biomass production.

TOPIC 4 Combining Different Species: Which System Design?

Separation of species in recirculating systems

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IMTA can be installed at sea or on land, in separate or mixed compartments. Land-based IMTA has several advantages, such as better control of flows (e.g. nutrients, energy); the ability to produce high-value species (e.g. microalgae); and less pressure from predators, pathogens, and extreme weather events. RAS-IMTA systems divide each species into separate production units, which allows environmental parameters to be adapted to the needs of each species. The challenge of new RAS-IMTA systems is to better understand and manage exchanges between the compartments, such as how to identify appropriate species that remediate fish waste and produce food for the next compartment, and how to identify and better control factors that influence productivity (e.g. pH, CO_2).

All species in one pond

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In pond-based IMTA that associates fish, oysters, phytoplankton, and macroalgae, phytoplankton plays a crucial role because they increase dissolved oxygen in the water, capture excess nutrients from animal excretion, and serve as food for the oysters. The oysters are also important since they control the density of microalgae and particulate matter in the ponds, which stabilizes the dissolved oxygen level and increases transparency of the water column. The increased transparency and pond fertilization due to oyster excretion helps phytoplankton to proliferate, which benefits the oysters themselves and the macroalgae. This ultimately improves water quality and decreases energy costs of water aeration.

The addition of oysters to traditional fishpond aquaculture improves fish production. Nonetheless, the competition for nutrients between phytoplankton and macroalgae should be considered when designing integrated production systems.

All species in one tank

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Interactions between marine species and improvements in environmental performances can be demonstrated in a single container.

European sea bass fed on an artificial diet were co-cultured with bivalves (mussels and oysters) and sea cucumber species (multi-trophic) in an open flow-through seawater reservoir for three months. This system was compared to a mono-trophic system (only sea bass) and a similar multi-trophic system in which fish were fed an unconventional diet (low in fishmeal).

The seabass had better growth performance in multi-trophic than mono-trophic culture. The former also reduced nutrient loads in the water and sediment, and modified the bacteria community in the sediment. High fish density influenced the growth of soft tissue in bivalves. The low fishmeal diet decreased fish and sea cucumber growth as well as sediment quality.

These results show the potential benefit of co-culture on seabass performance and water quality, as well as the interactions between the species in the system.

ALSO: What Contribution to Sustainibility?

Recommendations for decision makers

IMTA provides new opportunities for aquaculture development because it is less expensive, more robust, and more environmentally friendly. However, developing it remains a challenge that requires both empirical studies and scientific development, due to the complexity of interactions. There is no one-size-fits-all solution, but models of systems are emerging.
The mimicry of ecosystem functioning is a factor for acceptability by consumers and a source of satisfaction for producers and society. Diversification of products implies that producers will need to increase their knowledge and expertise. This increase in complexity is a risk factor that should be compensated by an increase in income. Diversification of markets can be an opportunity, but is also difficult to manage, depending on the size of the production system.
Specific support is required in different domains. Specific education and training should be developed, as should extension services. Scientific research should continue to focus on the variety of subjects associated with IMTA. There is a need for public authorities to recognize this activity and adapt policies at local and national levels.

The main lessons from environmental assessment studies

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By mimicking an ecosystem, IMTA should improve the use of feed inputs, produce more species in the same space, and decrease nutrient discharge into the environment (i.e. be more beneficial than monoculture systems).
However, how certain are we that IMTA is truly environmentally sound?
Life Cycle Assessment (LCA) considers the flows of matter and energy generated by a system to estimate several environmental impacts of the system. IMTA systems clearly decrease nutrient loss, increase nutrient recycling, and improve resource use. Therefore, they may have several environmental benefits, as shown for Azolla-Gourami culture. Nonetheless, these benefits depend greatly on the growth of each species and can be reduced drastically if not all compartments are harvested and sold. Since IMTA systems are technical systems, their environmental impacts are sensitive to management practices.

Stakeholder perceptions of IMTA

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Understanding the factors that are necessary for acceptability of IMTA should be based on the perceptions of these aquaculture systems. This understanding depends on the amount of information provided, the approaches of communication used, the institutions in charge of implementing the IMTA, and, more generally the stakeholders' sensitivity to the environment. Producers and stakeholders in France (49 respondents), Indonesia (82 respondents), Romania (72 respondents), and Greece (26 respondents) were surveyed to identify perceptions of IMTA and limitations to IMTA development.
IMTA was not widely known, except in Romania, where polyculture was practiced by 60% of the producers surveyed. Associations of fish-plants-invertebrates, fish-plants (macroalgae, macrophytes), or fish-plankton-invertebrates were cited most frequently as interesting prospects. Depending on the country, development of IMTA is challenged by regulatory restrictions; the availability of sites; and the implementation of technical, financial, and structural support for the profession. Finally, the contribution to certain regulating ecosystem services is widely perceived as an improvement in the image of the sector and a response to criticisms of intensive aquaculture.

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https://www6.inrae.fr/imta-effect

The IMTA-Effect Project

Project Summary

The objective of the IMTA-Effect project, supported by EU ERANET-COFASP, was to provide new knowledge to sustain development of IMTA using experimental and modeling approaches. Seawater ponds (fish + filter feeders + deposit feeders or macroalgae) were studied by IPMA in Portugal and HCMR in Greece. Rice-fish culture was studied by ISEM in Madagascar, and freshwater ponds in semi-separate systems for carp polyculture were studied by UDJG and Romfish in Romania, and for Azolla-Gourami in Indonesia. A compartmented IMTA that added planted lagoons to fish polyculture in freshwater ponds was studied by INRAE in France. Finally, RAS were studied by separating each species into specific tanks by AUA in Greece and by ISEM (fish and macroalgae) and Ifremer (marine fish, phytoplankton, oysters, and ragworms) in France.

The case studies showed that IMTA's adapted management of interactions among species of different trophic groups improved the aquaculture system. Compared to a reference fish monoculture, the overall productivity of the systems can increase due to the production of other products or services. The efficiency of delivering feed to fish increases overall by recycling in the system loop, which decreases the environmental impacts. IMTA also diversifies aquatic products, which can increase the robustness of aquatic farms. We demonstrated the key role of primary producers (plants, micro- and macroalgae) as the engine of nutrient recycling. One advance of the IMTA-Effect project was made in system modeling. We characterized the energy distribution (DEB) of ragworms and modeled the food web structure in pond systems using Ecopath with Ecosim, combined with the use of C and N isotopes, which trace the fate of nutrients in the food web. The IMTA-Effect project was an opportunity to strengthen the knowledge and diffusion of new practices in the aquaculture sector, thus opening new perspectives for development.

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