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Regional Integrated Multi-Trophic Aquaculture (RIMTA): Spatially separated, ecologically linked.

Running title: Regional Integrated Multi-Trophic Aquaculture

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Abstract

Aquaculture sustainability is restricted by environmental drawbacks such as the pollution derived from the released organic waste. Integrated multi-trophic aquaculture (IMTA) aims to lower the input of this waste by culturing other species of low trophic level which feed on them. Despite the appealing idea of IMTA, its implementation is very limited in marine ecosystems. Focusing on marine fish farming, in general terms, fish farm waste is not expected to constitute a relevant food source for low-trophic level organisms cultured in the water column. We propose Regional Integrated Multitrophic Aquaculture (RIMTA) as a shift of paradigm in the way IMTA is used to sequester the dissolved exported waste and derived primary production generated by high trophic level cultures. RIMTA advocates for independent allocation of cultures of low and high trophic level species within the same water body. RIMTA implementation should be economically supported through tax benefits or nutrient quota trading schemes. Moving from IMTA to RIMTA should not only foster aquaculture sustainability but also the circular economy and the ecosystem services that the low trophic level cultures provide.

Keywords: macroalgae and bivalve aquaculture, ecosystem-based approach, eutrophication, integrated coastal zone management, integrated multitrophic aquaculture (IMTA), organic matter pollution.

1. Environmental drawbacks of fed species aquaculture

The environmental degradation produced by aquaculture limits its sustainability. In the case of marine fish farming the pollution generated from organic waste can negatively affect marine habitats (Read and Fernandes, 2003). Organic waste mainly originates from uneaten feed and the faeces from cultured fish and are released in dissolved and particulate form (Sanz-Lazaro and Marin, 2008). The export of dissolved and particulate organic waste to the environment leads to eutrophication (Folke et al., 1994) and organic matter pollution (Sanz-Lazaro and Marin, 2008), respectively. Eutrophication can lead to the excessive proliferation of species such as microalgae and jellyfish (Vasas et al., 2007). Excessive inputs of organic matter deplete oxygen in the upper layer of the sediments, causing anoxic conditions, promoting anaerobic metabolic pathways and the production of the derived toxic by-products (Sanz-Lázaro and Marín, 2011). This leads to the deterioration of the status of benthic ecosystems (Karakassis et al., 2000; Ruiz et al., 2001; Sanz-Lázaro et al., 2011), and enhances the supply of nutrients to the water column, further contributing to eutrophication (Sanz-Lázaro et al., 2015).

2. IMTA, from tradition to the industrial era

The culturing of different species together has been performed for many years mainly in land-based aquaculture in Asia (Costa-Pierce, 2010). Traditionally, polyculture was in the form of small households in freshwater environments combining different fish species of fish with other organisms such as rice. Despite the possible benefits of the culturing of species in combination, in a polyculture one species does not necessarily feed on the wastes generated by another species (Soto, 2009).

Integrated Multi-Trophic Aquaculture (IMTA) comprises the culturing of species of different trophic levels, so species of low trophic level feeds on the organic waste produced by higher trophic level species (Neori et al., 2004; Chopin, 2013). High trophic level species are generally fish and crustaceans, while low trophic level ones are suspension feeders, detritivores and primary producers. In the last decades, Integrated Multi-Trophic Aquaculture (IMTA) has appeared as a promising tool to increase production, while mitigating environmental drawbacks. This concept is a win-win solution. IMTA aims to increase the yields of the species of low trophic level through the extra food supply, while reducing the input of organic waste, limiting the environmental impact (Soto, 2009).

As regards coastal IMTA, combining fish with macroalgae and bivalve molluscs arises as a promising concept to reduce dissolved and particulate waste from the water column, respectively. Predictive models (Ferreira et al., 2012; Sarà et al., 2012) along with laboratory and mesocosm studies suggest that fish farm waste can be a substantial source of food for macroalgae (Samocha et al., 2015) and bivalve molluscs (Handa et al., 2012a; Redmond et al., 2010) . But *in situ* studies using tracers such as isotopes of carbon and nitrogen or fatty acids, demonstrate that aquaculture waste constitutes a minimal source of food for macroalgae and bivalve molluscs (Aguado-Giménez et al., 2014; Handa et al., 2012b; Irisarri et al., 2014; Navarrete-Mier et al., 2010; Park et al., 2015). In enclosed areas, waste from aquaculture can be, to some extent, more important, but still constitute a minor fraction of their diet (Irisarri et al., 2015). Tentative explanations for these outcomes are that the trophic state of the water column and depth of the low trophic cultures are important variables for IMTA feasibility (Troell and Norberg, 1998; Cranford et al., 2013; Filgueira et al., 2017; Sanz-Lazaro et al., 2018). Nevertheless, fish farm waste remains a minimum source for low trophic level species disregarding the depth or trophic level of the water column in which they are cultured (Sanz-Lazaro and Sanchez-Jerez, 2017).

3. Why IMTA using macroalgae and bivalve molluscs does not seem to work as expected in open water areas?

This apparent mismatch between laboratory and *in situ* experiments is easily understood when considering the production system of fish farms and feeding biology of low trophic level organisms. First, marine fish farming generally involves relatively large juveniles and adults with generally one to two meals per day (Piper et al., 1986; Güroy et al., 2006). Since cultured fish mainly defecate just before feeding (Sanchez-Vazquez and Madrid, 2007; Oppedal et al., 2011), the exportation of organic residues to the water column mainly occurs during the feeding process (Troell and Norberg, 1998). Additionally, marine fish farms, aiming to minimize environmental drawbacks due to the export of fish farm waste, are located in sites with high hydrodynamism and water renewal (Sanz-Lazaro and Marin, 2008; Holmer, 2010). Thus, the availability of organic waste produced by fish farms is not only very abrupt, but also their persistence in these areas is low.

Second, in the case of bivalve molluscs, they have a diet preference for plankton rather than for non-living particles such as particulate organic matter (Shumway et al., 1985; Defossez and Hawkins, 1997). Additionally, their feeding rates are limited by the size, shape and speed of the available food (Walne, 1972; Safi and Hayden, 2010). So, natural seston concentration is more relevant for mussel feeding, than the short pulse input of organic waste from fish farming.

Due to the abruptness and high dispersion rates of the pulses of organic waste from fish farming, increases in nutrient concentration or its derived primary production are rarely reported in the vicinity of marine fish farm leases (Price et al., 2015). Despite so, a large part of the feed given to cultured fish ends up as waste. In the case of salmon, the production of one tonne of fish can result in a release of 136 kg organic carbon, 44 kg nitrogen, 8 kg phosphorous (Olsen et al., 2008). Taking into account that only Norway had a production above 1.4 million tonnes in 2019, we get an idea of the vast amount of waste that is being exported to the North Sea. Thus, the total contribution of dissolved nutrients to the water column has been estimated to be 32-36 % of nitrogen and 83-99 % of phosphorus in an estuary in Malaysia (Alongi et al., 2003), and 12 % of nitrogen in a fjord in Denmark (Christensen et al., 2000) and 5 % of the total inputs from anthropogenic sources in the Mediterranean (Karakassis et al., 2005).

The above-mentioned issues reconcile the apparent contradictions between laboratory and *in situ* outcomes of IMTA involving fish with macroalgae and bivalve molluscs. In general, marine fish farm waste constitutes a minor source of food for macroalgae and bivalve molluscs. Consequently, the yield of macroalgae and bivalve mollusc cultures, as well as their mitigation capacity towards dissolved waste, is not expected to be enhanced by placing low trophic cultures in close proximity to high trophic ones (Fig. 1).

4. From IMTA to RIMTA

4.1 Different type of waste, different scales for mitigation

Effective mitigation strategies against potential environmental drawbacks derived from aquaculture waste must follow an ecosystem-based approach taking into account suitable spatial scales according to the area of dispersion of this waste (Costa-Pierce and Page, 2013). Since particulate and dissolved waste have markedly different dispersion dynamics (Tett, 2008; Sanz-Lázaro et al., 2011; Jansen et al., 2018), adaptive scales should be considered depending on the type of waste.

In the case of particulate waste, bioremediation strategies should focus on the farm scale because their sedimentation mostly occurs in the first hundreds of meters from the aquaculture facility (Holmer et al., 2007; Sanz-Lázaro et al., 2011). Furthermore, suitable low trophic level candidates that are able to consume a substantial part of the particulate waste must be selected. Deposit feeders, such as sea cucumber, are good candidates, since they feed on the benthic system where particulate waste has a much higher persistence than in the water column (Cubillo et al., 2016). Thus, in this case, it is suitable to locate high and low trophic level cultures in close vicinity.

Dissolved waste is rapidly dispersed by currents. Thus, cultures that can sequester nutrients (macroalgae) or limit the derived primary production (bivalve molluscs), do not necessarily need to be in the close vicinity of the fish farms. These cultures need to be located in the area along which most of these nutrients or the derived primary production are dispersed, which is generally the water body area.

4.2 IMTA artificial boundaries: an enclosed concept used in open systems

IMTA concept of low trophic level cultures using the waste generated by high trophic level cultures justifies the location of both types of cultures in the close vicinity in closed systems, such as in terrestrial aquaculture ponds, or in very enclosed coastal areas. But locating low trophic level cultures in close vicinity to high trophic level cultures, aiming to sequester dissolved waste in an open system, is comparable to planting trees close to factories that emit CO_2, aiming to reduce their carbon footprint.

The apparently restricted feasibility of IMTA using bivalves and macroalgae in the water column is constrained by its implementation linked to the farm scale. The persistence of dissolved waste in fish farm leases located in open areas is so limited, that the ability of the low trophic cultures to assimilate them or the derived primary production is scarce. Thus, IMTA should be managed in terms of ecosystemic functionalities rather than absolute distances considering the scale of the reach of the waste (Chopin, 2013; Sanz-Lazaro and Sanchez-Jerez, 2017). In the case of dissolved waste, cultured macroalgae and bivalve molluscs can do their job even when these species are not in the close vicinity of the facility, as long as they are located within their area of dispersion.

4.3 RIMTA: Spatially separated, ecologically linked

Despite the above-mentioned recommendations, the localized concept of IMTA for dissolved waste has not been revised, and its implementation to industrial-scale keeps on being hindered by its own artificial boundaries, always culturing the species of low trophic level in close proximity to high trophic level species. IMTA should focus on the scale at which low trophic level species are able to sequester the waste generated by fish farming, which in the case of dissolved waste corresponds to the water body where it is located. Considering the spatial scales defined in ECASA toolbox (https://cordis.europa.eu/project/id/6540/reporting), typically IMTA has focused on zone A (local, farm-scale). However, IMTA using macroalgae and bivalve molluscs should move to zone B (small water body scale) and C (regional scale). The management of fish farms located in highly enclosed water bodies such as lakes, coastal lagoons, fjords and lochs, should be done at the scale of zone B; while off-coast and offshore farming should be done at the scale of zone C (Fig. 2).

We propose the concept of Regional Integrated Multitrophic Aquaculture (RIMTA) that is defined as *the culture of low trophic level species such as macroalgae and bivalve molluscs, to mitigate the ecological negative effects derived from the input of dissolved nutrients from fed aquaculture*. RIMTA is an ecosystem-based approach that takes into account the ecological processes, human-induced pressures and their respective spatial scales. Accordingly, RIMTA acknowledges that low trophic level species do not necessarily need to be placed in the close vicinity of the fish farm as long as it is located within the area of dispersion of the fish farm waste (Fig. 3).

Defining the scale and the boundary of a water body must be done carefully to assure that aquaculture leases, despite being spatially separated, they are communicated. Since this may not always be straight forward, in many cases, tracer studies or Lagrangian ocean analysis (van Sebille et al., 2018) should be required for a suitable site selection of macroalgae and bivalve culture leases. Examples of fish farm dissolved waste transport are already available (Venayagamoorthy et al., 2011).

RIMTA also acknowledges that the high dispersion of dissolved waste lowers the capacity of the low trophic level cultures to specifically feed on nutrients or the derived primary production released by high trophic level cultures. Additionally, nutrient input is a global anthropogenic driver of ecological change and several anthropogenic activities release nutrients to the environment (Halpern et al., 2008). Thus, irrespectively of the origin of the nutrients (from high trophic level aquaculture or from another anthropic source) that the low trophic cultures sequester, the low trophic culture will reduce the regional nutrient input or the derived primary production to which high trophic level aquaculture is contributing.

4.4 Implementation benefits of RIMTA

The balance of trade-offs between the benefits and costs of adopting IMTA is currently not sufficiently positive to motivate the IMTA implementation in Europe (Hughes and Black, 2016). This is partly due to the problems derived from culturing potential fouling species in close vicinity to fish farms, which can pose risks related to the increase of the biofouling in fish farm nets, reducing the water exchange and compromising fish health. RIMTA also facilitates the establishment of aquaculture facilities from a legal perspective. For example, in Europe, administrative processes and decisions dealing with aquaculture lease concessions are generally slow, especially for fish farms culturing different species (Hedley and Huntington, 2009). Monocultures have easier lease regulations in terms of bureaucracy and requirements which can speed up these administrative processes.

Separating both types of cultures will promote low trophic level aquaculture. This will not only foster the sustainability of low trophic level species, but of aquaculture in general. First, macroalgae and bivalve mollusc aquaculture do not need to be fed, releasing pressure to fish or other food stocks. Second, this type of farming facilitates local entrepreneurship, since the investment needed is low compared to other types of aquaculture. Third, macroalgae and bivalve molluscs are valuable food, being a source of protein- and omega-3, which can be directly used for human consumption or, indirectly, incorporated in formulated feeds for fish and other farmed species (Tiwari and Troy, 2015; Carboni et al., 2019). Consequently, low trophic level aquaculture can release pressure from agriculture and fisheries, activities with a stagnant production (DG RTD European Commission, 2017), and promote the farming industry.

4.5 Ecological interactions of RIMTA

The enhancement of macroalgae and bivalve mollusc aquaculture, apart from nutrient sequestration, can favour another key ecosystem service, such as climate change mitigation, through their use as biofuels (Hossain et al., 2008) or by acting as carbon sinks (Hill et al., 2015; Xiao et al., 2017). However, we need to keep in mind that the intensive cultivation of macroalgae and bivalves can lead to some negative ecological consequences.

The structures for culturing macroalgae and bivalve molluscs slow down currents, increasing the residence time of the water and sedimentation which may cause habitat modifications in the pelagic and benthic system (Buschmann et al., 2008). As regards bivalves, they need to be cultivated on appropriate densities, depending on the oceanographic conditions such as depth or current intensity to avoid environmental drawbacks in the benthos due to the release of particulate waste (Dumbauld et al., 2009; Fabi et al., 2009). Additionally, extensive bivalve cultures can lead to the depletion of planktonic organisms (Hulot et al., 2018). Thus, oceanographic variables related to potential benthic environmental drawbacks, such as current intensity or depth, as well as carrying capacities, should be taken into account in the location where the culture will be deployed (McKindsey, 2012). Caution should be taken in shallow, enclosed, eutrophic and low energy areas such as the Baltic since experts do not reach consensus on the suitability of bivalve aquaculture due to possible increased nitrogen benthic fluxes derived from organic deposition through pseudo-faeces (Cranford et al., 2007; Stadmark and Conley, 2011).

4.6 RIMTA sustainability

RIMTA, following an ecosystem-based approach, searches for sustainability integrating stakeholders in an equitable way. The full development of RIMTA must be associated with the recognition of the above-mentioned valuable ecosystem services, mainly nutrient and derived primary production sequestration, that macroalgae and bivalve mollusc cultures provide. Since these types of cultures can have a low monetary return compared to fed cultures, RIMTA should be accompanied by tax benefits for farmers that implement it or from nutrient trading schemes, which have already been proposed for reducing eutrophication in the Gulf of Mexico (Perez et al., 2013) or the Baltic Sea (Lindahl and Kollberg, 2009). Taxes on marine pollution (ecotaxes) provide incentives to polluters to reduce emissions and seek out cleaner and sustainable alternatives (Davis and Gartside, 2001). In our case, these ecotaxes would promote the sustainable use of natural resources, providing economical advantages to fish farm companies that lease low trophic cultures within the water body affected by fish farming. Thus, aquaculture companies will reduce the nutrient footprint or even become nutrient neutral, and indirectly, will lead to aquaculture diversification favouring the development of IMTA. Additionally, the nutrient sequestration produced by RIMTA would contribute to achieve a good environmental status in marine water bodies (Marine Strategy Framework Directive 2008/56/EC).The independent allocation of high and low trophic level cultures, followed by economical support, which should be explicitly supported by corresponding administrations through laws and regulations, is needed to ensure the implementation of RIMTA and its sustainability.

5. Conclusions

We present RIMTA as a shift of the paradigm in the way IMTA is used to mitigate the impacts of dissolved exported waste by the farming of high trophic level species.

RIMTA advocates for independent allocation of cultures of low and high trophic level species within the same water body, reducing the negative interactions among production systems. Based on an ecosystem-based approach, the scales used by IMTA are broadened to adapt them to the size of the water body. Accordingly, the nutrient and phytoplankton incorporated by low trophic level species should be included in the water body budgets. This separation will promote the development of low trophic level cultures. Nevertheless, this expansion should be done through an integrated coastal zone management approach. The carrying capacities for macroalgae and bivalve cultures need to be taken into account for the cultivation density along with the connectivity between high and low trophic level aquaculture facilities for the site selection. Economical support as tax benefits or nutrient quota trading scheme would support RITMA implementation. Moving from IMTA to RIMTA will not only foster aquaculture sustainability but also the circular economy and the important ecosystem services provided by low trophic level cultures.

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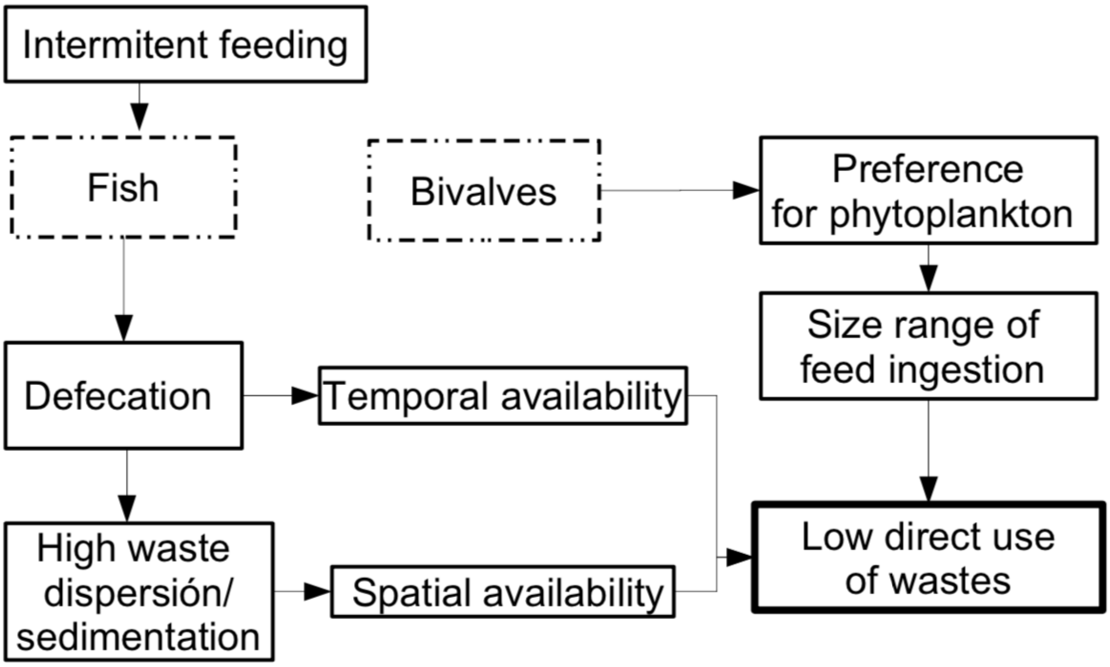
Figure legend

Fig. 1: Flow chart explaining the low resource availability derived from fish farming to low trophic levels cultured in integrated multitrophic aquaculture (IMTA).

Fig. 2: Spatial scales of integrated multitrophic aquaculture (IMTA) and regional integrated multitrophic aquaculture (RIMTA).

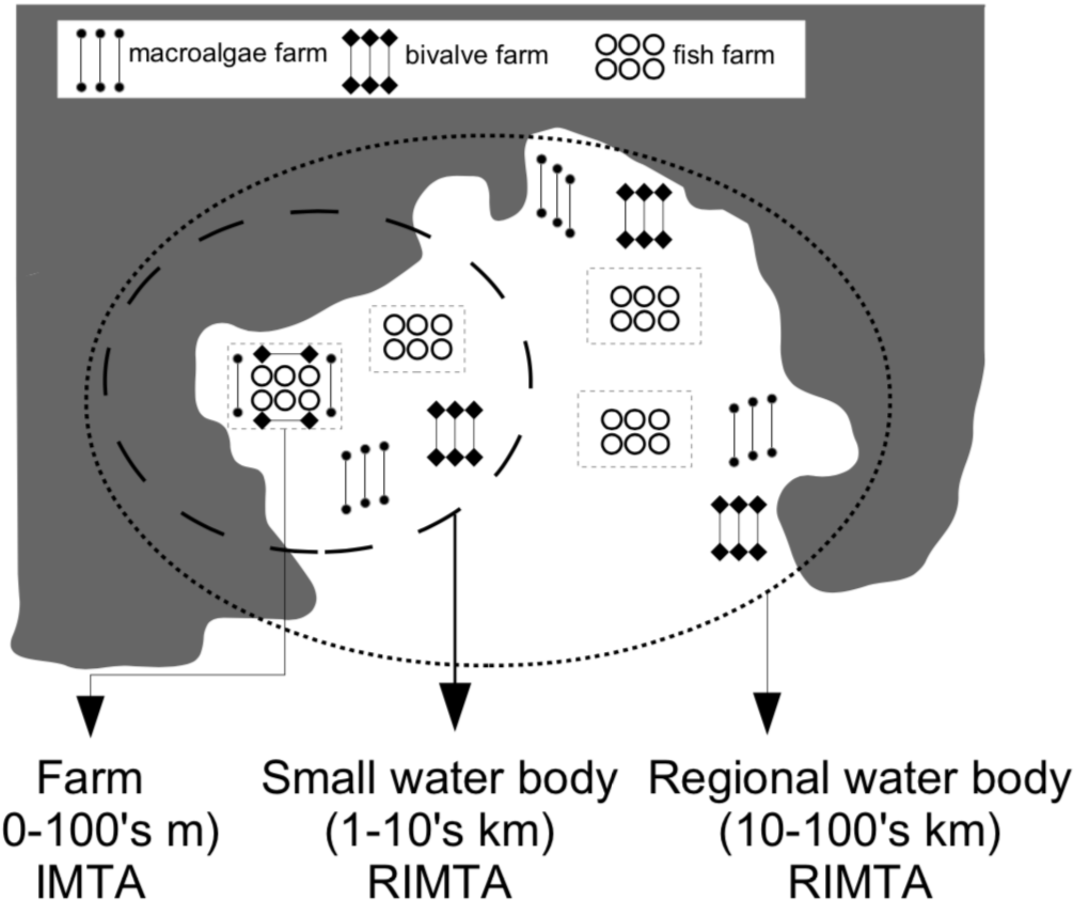
Fig. 3: Scheme comparing integrated multitrophic aquaculture (IMTA) and regional integrated multitrophic aquaculture (RIMTA) rationales. POM stands for particulate organic matter. Arrows indicate fluxes of matter.

Fig. 1



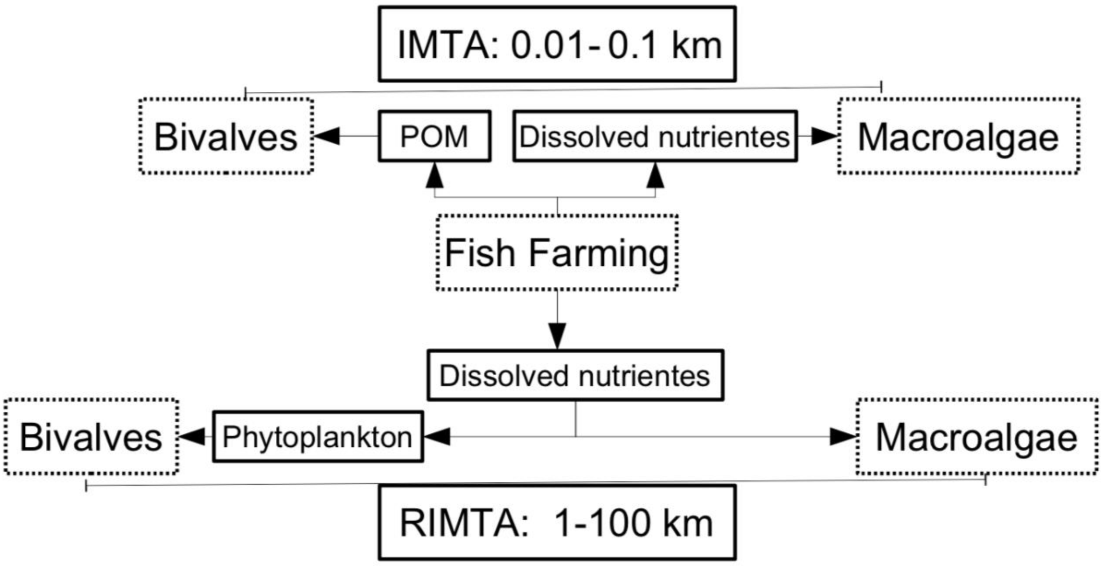
Intermitent feeding
Fish
Bivalves
Preference for phytoplankton
Size range of feed ingestion
Defecation
Temporal availability
High waste dispersión/ sedimentation
Spatial availability
Low direct use of wastes

Fig. 2



macroalgae farm
bivalve farm
fish farm
Farm
(10-100's m)
IMTA
Small water body
(1-10's km)
RIMTA
Regional water body
(10-100's km)
RIMTA

Fig. 3


IMTA: 0.01- 0.1 km
Bivalves
POM
Dissolved nutrientes
Macroalgae
Fish Farming
Dissolved nutrientes
Bivalves
Phytoplankton
Macroalgae
RIMTA: 1-100 km