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Going beyond the search for solutions: understanding trade-offs in European integrated multi-trophic aquaculture development

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ABSTRACT: There has been significant interest in the development of integrated multi-trophic aquaculture (IMTA) in Europe. Much of this interest has come from academia and regulators, and while elements within the European aquaculture industry have expressed an interest, to date, the adoption of the concept has been limited. Part of the attraction for regulators and academics is the ecological/economic win/win that is associated with eco-innovation solutions. However, if we are to understand why there has been limited uptake of IMTA in Europe, perhaps it is necessary to look at the issue in terms of trade-offs for the individual farmer or company. Using this viewpoint, we investigate the balance of trade-offs for the individual farmer or company to diversify from a traditional fin-fish production business into an IMTA system. In doing so, we reveal that the balance of trade-offs is currently not sufficiently positive to motivate the large-scale uptake of IMTA in Europe, and we contrast this against the situation in Asia where the balance of trade-offs gives better support for the adoption and practice of IMTA. By better understanding the trade-offs for the individual, it is possible to better understand the conditions that will promote the development of IMTA in Europe.

KEY WORDS: Cage culture · Eco-intensification · Integrated multi-trophic aquaculture · IMTA · Social licence · Extractive aquaculture

INTRODUCTION

Integrated multi-trophic aquaculture (IMTA) is both conceptually a simple idea and also highly appealing to regulators: the waste products from one food production process (in this case, fin-fish production) is acquired and assimilated by other organisms and converted into valuable products. This process both eliminates waste and increases the productivity of the food production system (Troell et al. 2003, Neori et al. 2004, Chopin et al. 2006). This win/win situation has its roots deeply buried in the eco-efficiency philosophy that aims to simultaneously increase both the economic and environmental performances of an industry or business (Ehrenfeld 2005). Alternately, IMTA can be thought of in terms of eco-intensification, where the productivity per unit input is increased (Amano & Ebihara 2005). In Europe, the model for fed fin-fish aquaculture has been very linear, in line with a fast replacement economy where the inputs to the industry lead to consumption of natural resources with high energy and water consumption, with externalised wastes. This is in contrast to the principles of IMTA, which aim to create an industry-based spiral or loop system (now termed the circular economy) that minimises energy

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flows, losses, and environmental deterioration, without restricting economic growth or social progress (Boulding 1966, Stahel 1982). The win/win that IMTA represents has been cited a number of times as a solution to some of the problems that are facing the European fin-fish aquaculture industry, such as ecological damage, economic stability, and dependence on commercial feed (Klinger & Naylor 2012, Chopin et al. 2013, Granada et al. 2015).

Despite a strong tradition in Asia (Chan 1993) and the fact that the IMTA concept in various guises has been in the scientific literature for at least 40 yr, since the early 1970s (Ryther et al. 1972, 1975, Ahn et al. 1998, Buschmann et al. 2001), there is almost no commercial uptake of IMTA in Europe. This is against an increasing academic interest in Europe in the concept of IMTA (OECD 2010). Given the significant uptake of the concept of the circular economy within Europe as a whole (World Economic Forum 2014) and the eco-efficiency potential of IMTA technology, this lack of uptake is, on the face of it, hard to understand. Several studies have elucidated possible reasons why there has not been a transition from academic promise to commercial reality (Troell et al. 2003, 2009) and have included reasons such as the performance of the extractive organisms or the economic performance of the systems. However, most previous studies have identified gaps in the scientific knowledge, but it will not be scientists who implement IMTA at a commercial scale, but rather companies and individuals within those countries. Therefore, this paper attempts to better understand the commercial motivation for the adoption of IMTA. The question is even more pertinent given the fact that aquaculture production in Europe is stagnating, with growth over the last decade only around 1% per annum (Anon 2009, 2015). This is in stark contrast to the picture in Asia, where aquaculture is the fastest-growing food production sector (FAO 2012) and IMTA is commonplace.

Here, we argue that there is a need to move past this win/win conceptual framework and its view that IMTA is a solution: this framework is flawed or at best is unhelpful. If we move beyond a solution-based mind-set, we may explain the contrasting implementation of IMTA in Europe and Asia. Instead of considering IMTA as a 'solution' for European aquaculture, it is perhaps better to quantify the trade-offs involved in its adoption. Sowell (1995) argued that in social systems, there are no solutions, there are just trade-offs between different conditions, situations or states. Thus, instead of thinking 'What will remove particular negative features in an existing situation to create a solution?', it is more useful to frame the question as 'What must be sacrificed to achieve this particular improvement?' (Sowell 1995). Instead of thinking of IMTA as a solution and wondering why there is no industry adoption of the technology, we consider the trade-offs between the benefits and costs of adopting IMTA at the level of an existing fin-fish farmer or company. Applying this analysis to regions where IMTA is more common, we can try to understand what needs to shift in that balance of trade-offs to foster the adoption of IMTA in Europe. For the sake of this thought experiment, we will assume the scenario of an existing European (including Norway) fin-fish farmer wishing to develop a simple system of IMTA consisting of fish, mussels, and seaweed in a temperate open-water system.

EXAMPLES OF TRADE-OFFS INVOLVED IN THE ADOPTION OF IMTA BY A EUROPEAN FIN-FISH PRODUCER

Increased productivity

One of the benefits cited for IMTA is an increase in productivity, but what does that really mean at the level of the farmer or the company? Already, fin-fish producers in Europe and especially salmon producers in the Atlantic have efficient, fully industrialised operations (Vassdal & Holst 2011, Asche et al. 2013a), and there is no mechanism for IMTA to increase the productivity of their fish operation *per se*. However, considering productivity per unit input and measuring other outputs as well as fish, there are real opportunities to increase productivity. This increase in productivity happens firstly because there is an increase in production from the lower trophic species that are grown alongside the fin-fish and secondly because there is good evidence to suggest that these lower trophic species are able to utilise the nutrient from the fin-fish and are more productive when grown alongside fed aquaculture (Lander et al. 2012, Sanderson et al. 2012, Irisarri et al. 2015), although this experience has not been universal (Cheshuk et al. 2003), indicating that the integration may require some tuning. Using a mass balance approach, the production of 1 tonne (t) of salmon releases approximately 50 kg of nitrogen into the environment (Wang et al. 2012), which could support the growth of 10 t of seaweed or 5 t of mussels over the course of the production cycle of the salmon (Holdt & Edwards 2014). In the case of seaweed, this equates to a 1000% increase in biomass (wet weight relative to the fish production) produced and an increase in protein production by 166% (based on the N content of fish being 3%; Wang et al. 2014). As such, there is a clear increase in productivity of the whole system per unit feed (if the farmer could convert 100% of emissions to product). However, to make this meaningful to the farmer, there needs to be a proven case that these products can be sold at above their production costs plus an acceptable margin.

There is a scenario in which IMTA may play a role in increasing feed efficiency of the main fin-fish species. The provision of feed is the single largest contributor to resource use and emissions from open-cage salmon production (Grosholz et al. 2015). If instead of framing productivity in terms of per unit feed, we frame it in terms of per unit of fish meal or fish oil from wild fish stocks (biotic depletion), then the recycling of nitrogen lost to the environment back into marine proteins and lipids, and the subsequent reincorporation into fish feed, offers opportunities to increase the productivity in a way that may be meaningful to the farmer. The incorporation of seaweed into fin-fish aquafeeds has been shown to be possible at an experimental level (Wahbeh 1997, Yildirim et al. 2009, Marinho et al. 2013). As previously stated, an IMTA system with 100% efficiency in capturing nitrogen would allow for significant protein production using seaweed or mussels, but in addition, there is the potential for significant production of marine lipids. From the 10 t (w/w) of seaweed produced for every tonne of fish, it would be possible to produce 164 kg of protein and 9 kg of marine lipids (based on the production of *Alaria esculenta*; Mæhre et al. 2014), and in theory, these components could be recycled back into fish feed. This has the potential to significantly reduce the environmental impact of the industry by further reducing reliance on marine proteins and lipids from wild-harvest fisheries. However, the reality is much more complex and logistical; legal (in Europe) and economic constraints make this unfeasible in the foreseeable future. Furthermore, it is unlikely that this recycling would be of benefit to the individual farmer in the short term.

Reduced environmental impact

In the eco-efficiency win/win, the second win is reduced environmental impact. This is achieved through the ability of the extractive organisms to make use of waste products of the fin-fish production as nutrient and energy. As such, these waste streams are assimilated into the tissues of the extractive organisms and are removed from the environment. In our scenario, there are 2 waste product streams of interest: dissolved nutrients and particulate organic matter (POM: fish faeces and uneaten pellets). The dissolved waste stream consists mainly of ammonia (Sanderson et al. 2008), which can be detected close to the fish cages but can quickly attenuate (Merceron et al. 2002). In the case of the POM, the physical extent of the plume of suspended particles is difficult to detect (Cranford et al. 2013) and may not extend much beyond a few hundred metres from the farm (Brager et al. 2015). Any direct ecological benefit with direct trophic transfer of nutrient needs to take place within this limited zone around the fish farm. Furthermore, the bioremediation potential within this zone has been shown to be limited for both mussels and for seaweed (Broch et al. 2013, Cranford et al. 2013). In addition, both mussel cultivation and seaweed cultivation have their own environmental impacts on the benthos (Eklöf et al. 2006, Wilding 2012, Ren et al. 2014). Therefore, IMTA is likely to increase the total benthic impact of any one farm, if that farm now incorporates mussel and seaweed production (Troell & Norberg 1998), but the benthic impact per unit of production (salmon plus mussels or seaweed) would be significantly reduced. However, if the benthic footprint of the fin-fish and the extractive organisms (the mussel or seaweeds) overlap, this would then in fact increase the environmental impact in this zone locally, through the additive effect of the deposition from the fin-fish and the deposition from the extractive organisms. Because fish farms are regulated regarding their benthic impact, this possible increase possesses a significant risk to the fin-fish producer.

Increased space requirement

Most fin-fish aquaculture in Europe is intensive (FAO 2012), while the extractive species usually used in IMTA are extensive cultures, with much lower levels of production per unit area. For example, cage culture of fish produces between 1125 to 1750 t ha^{-1}, mussels 76 t ha^{-1} and for aquatic plants 1 t ha^{-1} (Bostock et al. 2010), although other estimates (Hughes et al. 2012) give higher values for kelps. Because the availability of sites is cited as a limiting factor for the development of European aquaculture (IUCN 2009), the decision to use the available space for the production of anything other than the primary fin-fish product would seem a paradoxical decision for a fish farmer. This is further compounded by the value of those respective crops. Using FAO data, in Europe, the value of bivalves and aquatic plants per tonne is approximately 45% and 11%, respectively, of the value of fin-fish (FAO 2012). This is of course the value of the product and not the profit realised by the farmer. The availability of sites for aquaculture development is not a simple factor of available space but is entirely mediated through the local regulatory system, which designates the availability of sites. The availability of fin-fish sites may be partially or entirely decoupled from the availability of sites for extractive species or from IMTA sites, and therefore, the fin-fish farmer is not making a simple decision of fin-fish versus extractive species. However, given that effort must be expended both in gaining licences for fin-fish and for extractive species, the value per unit area of fin-fish would suggest that effort is better spent obtaining additional fin-fish licences where available. It has been estimated that the ratio of wet weight of kelp biomass to salmon required to sequester the nitrogen output of the salmon ranges between 6.7 and 12.9 depending on the kelp species: when converted into a space equivalent, this ranges between 0.1 and 0.13 ha per tonne of fish (Reid et al. 2013). In terms of sequestering 10% (as a nominal value) of the nitrogen from a 1000 t salmon farm, this would require approximately 10 to 13 ha of seaweed cultivation. These values are roughly in line with lower estimates for the space required to sequester 10% of the dissolved nitrogen from Danish fish farms (Holdt & Edwards 2014). Using these values and Bostock et al.'s (2010) estimates of space required for salmon production, 1 ha of salmon production would require between 17 and 23 ha of seaweed to sequester 10% of the nitrogen output. However, in their study, Holdt & Edwards (2014) argue that mussel cultivation is approximately 220% more efficient than seaweed cultivation per unit area (Holdt & Edwards 2014).

When considering these values in relation to the spatial configuration of an IMTA system, thought needs to be given to the large amount of sea room that modern fin-fish farming requires around the cages. With well boats now up to 75 m in length, there is the need for significant amounts of sea room around cage groups. This need combined with the extensive amount of space required for extractive organisms will mean that the majority of extractive organisms in an IMTA system will be outside the zone where the outputs from the fin-fish cages can be measured or any direct trophic linkage can be assumed. There is, however, a case in which this additional requirement for space that IMTA represents could be viewed as a benefit to the fish-farmer. There has been a general move from smaller to larger farms as the aquaculture industry has developed in Europe, and this shift has left a number of smaller farm sites vacant. As licenced sites have become scarcer, there has been increasing pressure from the regulators to bring these sites back into production. Because these smaller sites are no longer cost-effective for large producers, there is a risk that the sites will be reassigned to smaller producers. This reassignment is a significant risk to larger producers in terms of disease control and biosecurity, if those sites are in the same water body as their larger sites. One option for the large producer is to use these sites for non-fin-fish production of extractive species and for the sites to act as a 'fire break' between fin-fish sites in terms of bio-security. This use opens up another possibility that IMTA can be considered not just at a farm scale but also in terms of a water-body scale, where the direct trophic linkage between the fin-fish and the extractive organisms is unproven (or unprovable) but instead a mass balance approach is taken. In this approach, the amount of nitrogen that enters the system through the fin-fish cultivation is balanced against the nitrogen removed from the system by the mussels and seaweed, irrespective of actual distance, as long as they are within the same water body (Reid et al. 2013).

One important consideration for space and IMTA is the development of benthic IMTA, because this IMTA would probably sit within the footprint of the existing farm, and as such, the space requirements would be small (Robinson et al. 2011). Initial modelling studies show that benthic IMTA could well be an appropriate technology to improve productivity and to reduce benthic enrichment (Cubillo et al. 2016). However, the authors are unaware of any such technology commercially available in Europe at the moment.

Increased social licence

Currently, there is no legislative or regulatory requirement for a fin-fish producer to implement IMTA in Europe, despite legislation in Demark to reduce the environmental emission of fish farms, which is prompting IMTA development (Holdt & Edwards 2014). However, to operate effectively within a community and to expand, an industry requires a social licence to operate, going beyond what is just required for strict compliance with the regulation or law (Gunningham et al. 2004). One of the barriers to the development of aquaculture in Europe is limited access to new sites. The availability of new sites will ultimately be determined by how the fish-farming industry is thought of in the society in which it operates and how fish farming reflects the values of the society in which it operates (Hamouda et al. 2005), and it can be argued that aquaculture increasingly requires a social licence to operate (Leith et al. 2014). Negative public perceptions of aquaculture are based around the industrialisation of the ocean (Mazur & Curtis 2008) and the emissions associated with it (Katranidis et al. 2003) and the fact that the public prioritize the reduction of environmental damage associated with aquaculture (Whitmarsh & Wattage 2006). Public acceptance of aquaculture is a function of the perceived value in terms of economic benefit weighed against the negative perceptions, such as environmental degradation (Whitmarsh & Palmieri 2009).

The conceptually simple idea of IMTA with the win/win of reduced environmental damage and increased economic benefit offers the opportunity to shift this perceived balance toward increased benefit and reduced pollution and so increase the social licence of IMTA-related aquaculture. This effect has been shown in a number of studies where, after explanation of the principles of IMTA, there is an increase in positive social perceptions (Ridler et al. 2007, Barrington et al. 2010). This pathway from better environmental performance to increased social licence to increased availability of aquaculture licences can already be seen in Norway, where the Norwegian government has created 45 'green aquaculture' licences in 2013 (Nikitina 2015). These licences are subject to strict environmental criteria on sea lice, escape risk, and other controls of environmental impacts.

Increased complexity

Much of the fin-fish aquaculture in Europe is highly industrialised and optimised, and profit margins on the fish have historically been somewhat volatile (Andersen et al. 2008, Asche et al. 2013b, Iotti & Bonazzi 2015). Adding more species to a site will add new layers of complexity to the system. If the fin-fish operation (the core business) is to remain profitable, it is crucial that these new complexities do not reduce the efficiency of the fin-fish production. Some of these complexities are logistical in terms of the additional infrastructure that is required, such as mussel and seaweed longlines. As previously discussed, any impingement of the IMTA infrastructure on the requirement of large boats or ships to access the fin-fish cages may reduce the efficiency of the fin-fish operation. There will also be an increase in the complexity of the biosecurity of the site when dealing with organisms with different production cycles. Disease is a major constraint on the industry, costing the industry as a whole approximately $US6 billion annually (Brummett et al. 2014), so any new production system must not increase the risk of disease. There is a lack of clear evidence about the role extractive species may play as a reservoir for infectious agents or the role they may play in eliminating or reducing the risk of disease. In the case of *Vibrio anguillarum* (vibriosis), blue mussels *Mytilus edulis* were shown to accumulate the vibrio in their digestive glands (Pietrak et al. 2010). Mussel pseudofaeces contained concentrated and infectious *V. anguillarum*. Juvenile cod exposed to infected faecal material suffered 60 to 80% mortality. This result indicated that in the co-culture of mussels and fin-fish, mussels may act as a reservoir of infections for *V. angillarium* (Pietrak et al. 2010). However, in the case of infectious salmon anaemia virus (ISAV), blue mussels were shown not to accumulate the virus and may deactivate the virus (Skår & Mortensen 2007, Molloy et al. 2014). There has been significant interest in the ability of bivalves to ingest sea lice larvae (Molloy et al. 2011, Webb et al. 2013), and if the efficacy of this as a lice-control method could be proved, it would be a big driver for the adoption of IMTA by salmon farmers. Another important component when considering increased complexity is the human resource capacity within any one farm or company. Fin-fish farming, shellfish farming, and seaweed farming are all skilled professions, and while there is a degree of complementarity in the skill sets among the 3, there are also large differences in required skills. A fin-fish farmer may need to 'buy in' expertise from outside, creating further complexity and cost.

Increased profitability

Full and comprehensive economic analyses of integrated aquaculture are difficult to find for European or western context. The existing studies are based on models, and simulations suggest that IMTA can increase the profitability for the individual operator when the market conditions are right and can provide a measure of resilience during periods of unfavourable conditions (Whitmarsh et al. 2006, Ridler et al. 2007). However, both these studies are based on hypothetical farms. A study from Sanggou Bay, China, based on real data and not models, showed that there was a significant increase in profitability in an IMTA operation based on scallop and seaweed production, compared to monocultures of those species alone (Shi et al. 2013). The other route to increased profitability for a fish farmer is if s/he can sell his/her main products for more as a result of being produced through IMTA. In a public perceptions survey of integrated aquaculture (Barrington et al. 2010), restaurateurs stated that they would be willing to pay up to 10% more for environmentally friendly seafood. Another survey showed that 38% of New York seafood consumers would be prepared to pay 10% extra for IMTA produced mussels if they carried appropriate labelling (Shuve et al. 2009). However, it is impossible to predict if these results would be borne out in a real marketplace.

HOW DO THESE TRADE-OFFS COMPARE WITH THE SITUATION IN ASIA?

At a very gross level, a first-order calculation shows that in Asia, the balance of fin-fish aquaculture to extractive aquaculture (where molluscs and aquatic plants categories from the FAO database are considered extractive organisms) is approximately 1:1, whereas in Europe, it is 3.5:1 (FAO 2012). This difference coupled with a higher relative value of extractive organisms (molluscs and seaweed in Asia compared to fin-fish; FAO 2012) means that the economic case for choosing a production system that boosts the growth of extractive organisms is much stronger. As such, there are fundamental differences in how these trade-offs impact the industry in Asia. While there is no increase in productivity for fin-fish under IMTA, there is evidence to support the benefit to shellfish and seaweeds, which are a larger proportion of the Asian industry and have a higher value to this industry. Also, in Asia, the main area of environmental concern for the aquaculture industry and regulators is the impact associated with aquaculture and the water column as opposed to the benthic impacts (Hu et al. 2010, Keesing et al. 2011), and the link between IMTA (seaweed and mussels) and reduced environmental impacts is much clearer for the water-column impacts than for benthic impacts. In terms of the negative trade-offs, the increased space requirement is less of an issue to an industry more biased toward extensive production, and the increase in complexity of an IMTA operation is more manageable with a less-mechanised and more labour-intensive industry that is characteristic of Asian aquaculture. From this initial characterisation, it would appear that the trade-offs for IMTA are more positive for Asia compared to Europe (Table 1). For the European industry to embrace IMTA, there needs to be development of economically and technically viable benthic IMTA which will ameliorate the seabed impact of fin-fish culture. There also needs to be a better financial case made for the adoption of IMTA based on empirical evidence. This, combined with an increased social licence for companies practicing IMTA that translates into a greater licenced area and biomass, would significantly increase the development of IMTA in Europe.

Table 1. The relative balance of trade-offs associated with IMTA in Europe and Asia

	Europe	Asia
Positive trade-off (for individual company)		
Increased productivity	No benefit to core business (fin-fish) Relatively lower value of extractive species	Benefit to core business (shellfish and seaweed) Relatively higher value of extractive species
Better environmental performance relative to industry's concerns	Not proven for most environmental impacts, likely to increase main environmental constraint (benthic footprint)	Evidence for improved water quality (main environmental constraint)
Increased social licence	Evidence to support	No evidence
Increased profitability	Not proven	Evidence to support
Negative trade-offs		
Increased space requirement	Availability of space is a major constraint to the industry development, with limited opportunity to increase production per site due to regulation	Availability of space is a major constraint to the industry development. Limited space is driving an increase in productivity
Increased complexity	Highly industrialised industry less able to deal with increased complexity	Less industrialised production, with higher levels of human labour and therefore greater flexibility

CONCLUSION

If IMTA is to be adopted by an individual farmer, the trade-offs will have to provide a net benefit or, to paraphrase Sowell (Sowell 1995), 'What must the finfish sacrifice in order to achieve the benefits of IMTA?' There are plenty of examples of where other industries have seen this balance of trade-offs as positive and have developed new environmental standards that have increased productivity and reduced environmental damage (Porter & Van der Linde 1995, Florida 1996). The question then rises how the trade-offs are weighed to determine if there is a positive balance to the adoption of IMTA by society. It is important to note that these trade-offs and their weight is entirely scale- and context-dependent (McShane et al. 2011) and will vary according to national and international market conditions or regulations. Currently, there are few regulatory drivers in Europe to incentivise the adoption of IMTA at the level of an individual or a company. In fact, at the moment, the balance of trade-offs seems to be against the individual farmer adopting IMTA. For this to alter for the individual farmer, there needs to be a greater body of evidence of a financial benefit to the farmer, better systems to reduce the increase in complexity, and better support from policy and regulation to reinforce the increase in social licence associated with IMTA. If these trade-offs were to be considered at a national level or at an industry level, the outcomes might well be dramatically different. It is beyond the scope of this paper to make that weighing for any individual company, but it is possible to look at where the balance of evidence lies for both Europe and Asia and see some of the reasons why IMTA may be more prevalent in Asia and what needs to change in Europe before IMTA is more widely adopted.

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