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The economics of Integrated Multi-Trophic Aquaculture: where are we now and where do we need to go?

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Abstract

In integrated multi-trophic aquaculture (IMTA), species from different trophic levels are raised in proximity to one another and the co-products (organic and inorganic wastes) of one cultured species are recycled to serve as nutritional inputs for others. IMTA can reduce the ecological impacts near aquaculture operations, improve social perceptions of aquaculture and provide financial benefits for aquaculture producers via product diversification, faster production cycles and price premiums on IMTA products. We review aspects of IMTA's economic potential and market acceptance and consider ways to address the current gaps in our understanding. We find that adopting IMTA raises the assimilative capacity of the farm and that IMTA substantively reduces the environmental cost of aquaculture. Moreover, integrating extractive species (e.g. invertebrates and/or seaweeds), with existing fed-monoculture operations, can increase farm profits. The presence of positive public attitudes towards IMTA, as expressed by a willingness to pay a premium for its products, can further increase the profitability of adopting IMTA. Areas requiring more economic research include the development of comparative bioeconomic models of IMTA and the evaluation of competing production systems and their ability to internalize externalities to demonstrate the true value of IMTA to society. Further exploration of economic incentives, such as instruments needed to foster adoption of IMTA, and investigation of marketing opportunities, such as promoting the eco-certification of IMTA products, are also needed. Our paper aimed to inform economists and non-economists alike about the latest developments in IMTA economics, and spur further research on critical topics concerning this important subject.

Key words: environmental impacts, new production technology, non-market valuation, sustainable aquaculture, willingness to pay.

Introduction

Integrated multi-trophic aquaculture (IMTA) is an exciting development in the effort to find more sustainable ways to produce food from the sea. In IMTA, species from different trophic levels are raised in proximity to one another and the co-products (organic and inorganic wastes) of one cultured species are recycled to serve as nutritional inputs for others. We review aspects of IMTA's economic potential and market acceptance and consider ways to address the current gaps in our understanding. We find that adopting IMTA raises the assimilative capacity of the farm and that IMTA substantively reduces the environmental cost of aquaculture. At the same time, integrating extractive species (e.g. invertebrates and/or seaweeds), with existing fed-monoculture operations, can increase farm profits. The presence of positive public attitudes towards IMTA, as expressed by a willingness to pay a premium for its products, can further increase the profitability of adopting IMTA. Areas requiring more economic research include the development of comparative bioeconomic models of IMTA and the evaluation of competing production systems and their ability to internalize externalities to demonstrate the true value of IMTA to society (Granada *et al.* 2018). Further exploration of economic incentives, such as instruments needed to foster adoption of IMTA, and investigation of marketing opportunities, such as promoting the eco-certification of IMTA products, are also needed. Our paper aimed to inform economists and non-economists alike about the latest developments in IMTA economics, and spur further research on critical topics concerning this important subject.

Integrated multi-trophic aquaculture can improve the sustainability of seafood production, by reducing ecological impacts in proximity to intensive aquaculture operations, improving social perceptions of aquaculture and providing financial benefits for aquaculture producers via product diversification, faster production cycles and price premiums on IMTA products.[1] While we primarily address the economic and financial dimensions of IMTA, we also touch on its social and market acceptance. We examine the current state of knowledge concerning the economics and profitability of IMTA, and then further investigate a wider range of economic issues, including market implications, willingness to pay (WTP) for IMTA products and related issues. Moreover, in the interest of advancing research on the economics of IMTA, we outline several areas where new research is under way or needed; these include integrated modelling of IMTA and comparative production systems, incentives and instruments needed to foster adoption of IMTA, and related marketing issues such as promoting the eco-certification of IMTA products.

A few initial thoughts will lay the groundwork for the following sections. First, any assessment of the economic viability of a new technology must consider the 'economic' benefits from society's point of view, as distinct from the profitability of the technology for private operators. In the former case, all costs and benefits need to be considered, whether these relate to the farm operator (e.g. revenues) or to other parties (e.g. environmental, social and health benefits and costs). This approach is critical to determining whether adopting a new technology makes society better off or worse off. In contrast, profitability only concerns the farm operator (and investors) and reflects the tax and other financial considerations ignored in an analysis from society's perspective but vital to private decisions about whether to adopt the new technology. An ideal new technology would display both societal and private net benefits, but this is not always the case. We consider both perspectives in reviewing the relevant literature and presenting our later assessments and suggestions for further research.

At heart, the development of a food production technology such as IMTA is an economic problem, since it recognizes the economic impediments of monocultures in the form of negative 'externalities', an economic term used to describe the environmental impacts from production that are imposed on others and not accounted for in the production cost.[2] However, the nature of IMTA as a production system is complex. On the one hand, IMTA addresses some of the environmental issues associated with conventional monoculture aquaculture systems. On the other hand, under favourable circumstances it also can increase profitability from the private operator´s point of view, since it may reduce costs and add sources of revenue to the farm operation. This dual role of IMTA (and similar technologies) may present challenges from a public policy perspective. For example, if IMTA appears to be at least marginally financially profitable without supportive policies, policymakers may be less inclined to provide support in the form of subsidies or fiscal benefits. Yet only if such supportive policies are adopted will externalities, such as nutrient discharges, be properly 'internalized' into the production costs of aquaculture products, thereby giving less polluting technologies an advantage over technologies that do not address external costs. Policies that avoid addressing these externalities could lead to unsustainable developments, that is developments whose growth and longevity are limited by environmental, resource and social issues (Frankic & Hershner 2003).

Understanding the above arguments in principle is easy enough, but sound policy requires empirical assessments of the magnitudes involved. Once a subsidy or related economic policy to support IMTA is justified, the instruments for its implementation remain to be determined. Integrated economic and ecological modelling of IMTA and comparative aquaculture systems can help uncover these details by making assumptions and relationships explicit. Increasingly, modelling of aquaculture systems not only integrates economics with ecology but also incorporates the social dimension (Knowler *et al.* 2009). Bioeconomic modellers are ideally suited to carry out such research, but only a

[1]For example, see Chopin *et al.* (2001), Whitmarsh *et al.* (2006), Ridler *et al.* (2007), Barrington *et al.* (2010), Shi *et al.* (2013) and Alexander *et al.* (2016a).

[2]More formally, by 'externality', economists mean: 'a cost or benefit which affects a party who did not choose to incur that cost or benefit' (Buchanan and Stubblebine 1962).

modest amount of this form of integrated modelling has been applied to IMTA to date.

On the production side, it is necessary to evaluate the response of producers to the IMTA concept, the motivations that can encourage them to deploy IMTA and also the response of the entire market chain. It is not enough for modellers and policymakers to design producer incentives for a new technology in isolation, since market acceptability should be evaluated as well. For example, shellfish products that are cultured alongside waste streams in finfish-based IMTA systems may be attractive to some consumers for its improved environmental performance, while others may have concerns with regard to the quality of IMTA-grown shellfish. Only careful market investigations and empirical work can answer these questions, and so far, only a modest amount of this type of research has been undertaken.

In the following section, we commence with a review of the existing knowledge of the economics of IMTA, revealing that, while not extensive, there is a growing body of research work in this area. Subsequent sections are loosely collected under the heading: 'Closing the Gaps', and consider a variety of emergent or necessary topics for new research. It is hoped that in this way our paper will help bring economists and non-economists alike up to date on the state of knowledge but also spur further research on critical topics concerning the economics of IMTA.

What have we learned so far?

Research involving IMTA economics has focussed on issues such as the variety of benefits for the grower, the consumer and society that arise with the adoption of IMTA systems (Nobre *et al.* 2010). For example, IMTA can stabilize seafood supply through greater product diversity and reduced market risks associated with price volatility (Ridler *et al.* 2007) and increase job diversity by providing high paying jobs for highly trained personnel, while offering lower-skilled jobs for untrained people in peripheral locations, as detailed in a case study of South African abalone farming (Robertson-Andersson 2007). Food security may be enhanced as extractive products (e.g. invertebrates, seaweeds, detritivore fish and vegetables in freshwater aquaponics) may be affordable for local consumption, while the primary products (e.g. high-value fish and shrimp) are exported for foreign currency. Adopting IMTA also raises the assimilative capacity of the farm and its environment; this is probably why IMTA takes place on a large scale in China, with its restricted space for marine aquaculture (Troell 2008; Xiang 2015). Similarly, conversion of feed to commercial products is improved and there is better health of the primary species (Pang *et al.* 2006; Troell 2009). A better public image arising with IMTA may lead to easier access to government-issued operating permits and better relations with NGOs and local communities (Allsopp *et al.* 2008). In this section, we provide a selective summary of this field of research.

Economic analysis of IMTA

Only a few studies have undertaken a complete economic analysis of an IMTA production system, including taking account of external costs and benefits. For example, Chopin *et al.* (2001) valued the external cost of nutrient discharge associated with salmon monoculture, using information from a technical and economic cost–benefit analysis (CBA) of a land-based salmon-seaweed farm in Chile (Alvarado 1996). The authors used solid and dissolved waste loads and the cost of waste treatment to value the external cost of nutrient discharge from the farm (Folke *et al.* 1994; Buschmann *et al.* 1996). Chopin *et al.* (2001) estimated the annual environmental cost of 250 tonnes of gross fish production to be USD 201 441, decreasing to USD 64 000 when an IMTA configuration was adopted to internalize this environmental cost. Later work by Chopin (2011), Rose *et al.* (2014), and Kambey and Chung (2016) was used to value nitrogen removal in a mix of possible land-based IMTA systems considering abalone, finfish, seaweeds and sea cucumbers. Kambey and Chung (2016) used a STELLA model to generate physical values and a hypothetical nutrient trading credit (NTC) approach to assess the economic benefits from production and biomitigation; however, the methodology used is unclear and consolidated economic results for entire systems are not reported.

Several studies have valued the external environmental costs and benefits associated with conventional and improved aquaculture practices in China. Zheng *et al.* (2009) conducted a CBA of mariculture in Sanggou Bay, China, that analysed aquaculture operations producing extractive species. They considered how these operations affected four ecosystem services: food production, oxygen production, climate regulation and waste treatment. Using a standard CBA approach, the authors found largely positive impacts from mariculture in Sanggou Bay on ecosystem services and social benefits. An additional assessment showed significantly higher economic and environmental sustainability for IMTA than for the major two monoculture models in the same region (Shi *et al.* 2013). The study favoured the application of IMTA in the open-water systems in China on economic grounds.

Researchers have applied economic analysis to IMTA systems outside of China as well. Nobre *et al.* (2010) applied the Drivers–Pressure–State–Impact–Response (DPSIR) approach, in comparing an abalone monoculture system to an abalone-seaweed IMTA system from both an ecological and economic perspective. The authors used data from a South African land-based commercial abalone farm as a case study. From a firm's perspective and under the regulatory environment in place at the time, an abalone-seaweed IMTA operation increased profits by 1.4–5%, compared with a monoculture abalone operation. The authors also valued the net social benefits of adopting IMTA arising from reductions in nutrient discharge, natural kelp bed degradation and greenhouse gas (GHG) emissions and found their collective value to be several times larger than the net gain in profits alone. The farm's total benefit from adopting IMTA was estimated to be between USD 1.1 and 3.0 million per year (Nobre *et al.* 2010). These values considered differences in profitability between monoculture and IMTA, as well as the start-up cost of adopting IMTA and the value of reduced environmental externalities. The results suggest significant increased benefits from the integrated aquaculture system in a regulatory-economic environment that rewards reductions in externalities.

In conclusion, several studies have considered the external environmental costs and benefits of IMTA systems, but this research is too limited to provide a clear picture of the environmental benefits provided by IMTA. This represents an area of research that needs further investigation.

Financial profitability and IMTA

The majority of literature on the economics of IMTA has focussed on the financial dimensions of IMTA from the farm operator's perspective. Clearly, financial profitability is a critical factor for successful IMTA implementation at the commercial scale. In one study, Petrell and Alie (1996) developed a spreadsheet model of an integrated salmon-seaweed system to determine the financial profitability of growing seaweed in close proximity to salmon aquaculture operations. The authors considered two species of seaweed, *Laminaria saccharina* (now *Saccharina latissima*) and *Nereocystis luetkeana,* grown in different areas of the farm, either between the rows of salmon cages or 30 metres away from the outer edge of the farm cages. Results demonstrated that producing both species was financially profitable in most locations. Furthermore, in an analysis of an integrated salmon-seaweed production system in southern Chile, Troell *et al.* (1997) analysed the addition of *Gracilaria chilensis* cultivation near a salmon farm. The seaweed production added USD 34 000 per year to the farms' revenues, that is about USD 0.28 per kg of fish. Troell *et al.* (1997) concluded that the IMTA configuration contributed significant economic benefits to salmon farming in Chile, in addition to the obvious environmental advantages.

Similarly, Whitmarsh *et al.* (2006) investigated the financial profitability of a salmon-mussel production system using baseline data from Scottish mussel and salmon aquaculture farms (with no seaweeds). The authors used a capital budgeting model to compare the performance of three different systems over a 20-year time horizon: salmon monoculture, mussel monoculture and integrated salmon-mussel culture. They calculated a net present value (NPV) for the integrated system of USD 2.63 million, and this was greater than the combined NPVs for both the salmon monoculture system (USD 1.7 million) and the mussel monoculture system (USD 0.650 million), assuming mussel production rates were 20% higher in the integrated system. The additional financial benefit associated with the integrated system was termed an 'economy of integration'. However, the integration benefit was sensitive to price changes. A 2% per year decrease in salmon prices, holding all else constant, made an investment in the integrated system unattractive. Therefore, it was concluded that investing in an integrated system, while attractive, was risky.

In contrast, Ridler *et al.* (2007) found that adopting IMTA as a three-species system in a Canadian salmon farm not only increased profitability but also reduced the economic risk associated with production variability and changing market conditions. Using a capital budgeting model, they compared the financial viability of an IMTA system and a salmon monoculture, based on data from a pilot salmon–mussel–kelp farm in Eastern Canada. Over a 10-year period and assuming a 5% discount rate, the NPV for the IMTA system (USD 3 296 037) was 24% higher than the NPV of the monoculture operation (USD 2 664 112).[3] These results indicate that feeding the waste of one crop to another could increase profits. In a sensitivity analysis with all product prices reduced by 12% for the 10-year period, the IMTA system still generated a profit margin of 3.2%, whereas the salmon monoculture system generated a profit margin of only 0.3%. Additionally, three scenarios tested the variability of salmon harvested over the 10-year time horizon due to disease and/or weather conditions. The analysis revealed that under all three scenarios, the IMTA system was more profitable, pointing to the benefit of product diversification and a consequent reduction in production risk.

More recently, Carras *et al.* (2019) updated and extended Ridler *et al.* (2007). Using a discounted cash-flow analysis, they estimated the financial returns from investing in (i) a conventional monoculture with Atlantic salmon; (ii) an IMTA operation with Atlantic salmon, blue mussel (*Mytilus edulis*) and kelp (*Saccharina latissima*); and (iii) an

[3]The discount rate is a factor by which future net benefits of a project are reduced (discounted) so as to compare them to the present value of investment costs. For the purpose of any private project where returns are to be maximized, the relevant market interest rate is usually adequate for the discount rate. For public projects, discount rates usually differ from any of the prevailing market interest rates and are adjusted to reflect society's preferences.

Reviews in Aquaculture (2020) **12**, 1579–1594

IMTA operation with Atlantic salmon, blue mussel, kelp and green sea urchin (*Strongylocentrotus droebachiensis*), where the latter species served as a benthic component positioned beneath the net pens. The authors found that IMTA comprising three species was more profitable than both Atlantic salmon monoculture and IMTA composed of four species and that the four-species IMTA provided a lower NPV than salmon monoculture unless there was a price premium for IMTA salmon and mussels. When a 10% price premium on IMTA salmon and mussels was included, there was a substantially higher NPV for three-species and four-species IMTA compared with salmon monoculture. Given the research reported below regarding the good prospects for price premiums on IMTA products, it seems reasonable to view the NPV calculations with a 10% price premium as more credible.

Financial studies of IMTA generally indicate that integrating shellfish and/or seaweeds with existing salmon monoculture operations can increase farm profits while reducing environmental costs and generating environmental and social benefits. Not all financial analyses of IMTA systems have studied salmon farming, although these are the most common IMTA systems evaluated. For example, Fonseca *et al.* (2015) estimated financial returns from an integrated shrimp–oyster IMTA system with an added seahorse production component. Overall, they found the addition of seahorses to be profitable, yielding an internal rate of return (IRR) of 131.1%.

Bunting and Shpigel (2009) evaluated the financial potential of adopting 'horizontally integrated land-based marine aquaculture' using a bioeconomic modelling approach. The study considered two different systems. The first system was a temperate water system developed in France to grow fish, microalgae, shellfish and a polishing lagoon; this system did not show a positive IRR over a 10-year project life, except in the case where land and labour opportunity costs were left out and a 20% price premium was assumed for the product. The second system was a warm water system developed in Israel to grow sea urchins, shrimp and a halophyte (*Salicornia* sp.); assumed annual production of one million sea urchins produced a very attractive IRR of between 18% and 133% over the 10-year project life, depending on assumptions about sea urchin mortality and *Salicornia* yield. A second study on land-based IMTA examined potential aquaponics systems in Egypt, using the Integrated Recirculating Aquaculture and Hydroponics System (IRAHS) to grow fish, crustaceans and molluscs (i.e. tilapia, Nile catfish, grey mullet, freshwater prawns and clams) and greenhouse vegetables (Goada *et al.* 2015). Various configurations were investigated; all exhibited positive net income based on estimated returns on sales and costs.

Table 1 Per cent of survey respondents willing to pay varying price premiums for IMTA-produced mussels (Shuve *et al.* 2009)

Price scenario posed to respondents	Yes	No	Don't know
Pay same price (*N* = 639)	61	8	31
Pay 10% premium (*N* = 595)	38	21	41
Pay 20% premium (*N* = 471)	18	35	47

Those who responded *Yes* or *Don't know* to the current price were asked whether they would pay a 10% premium. Those who responded *Yes* or *Don't know* to the 10% premium then were asked whether they would pay a 20% premium.

Market demand, social acceptability and willingness to pay for IMTA products

A further area of economic research relating to IMTA concerns market demand and WTP for IMTA products.[4] To date, this research has largely concentrated on markets in Canada and the United States, with more recent attention being paid to Europe. For example, Barrington *et al.* (2010) looked at whether consumers of IMTA products in Eastern Canada consider them safe to eat. Not only did the authors find that consumers see these products as safe, but 50% of the respondents in their market survey were willing to pay a 10% premium for IMTA-labelled products. Additionally, Shuve *et al.* (2009) conducted a market analysis in New York City to determine whether mussels produced in an IMTA system could command a price premium; they concluded that consumers would pay a price premium for IMTA mussels (Table 1). Ultimately, the Barrington *et al.* (2010) and Shuve *et al.* (2009) studies revealed that a price premium for IMTA products is a realistic possibility in Eastern North America.

More recently, Kitchen and Knowler (2013) surveyed oyster consumers in San Francisco and used the contingent valuation method (CVM) to compare the WTP for oysters produced from IMTA and conventional methods. Their analysis revealed a WTP that is 24% to 36% higher for IMTA oysters compared with conventionally produced oysters. Using the contingent behaviour method (CBM), Martínez-Espiñeira *et al.* (2015) suggest that Canadian salmon consumers would derive benefits of at least CAD 280 million per year for the first 5 years after the introduction of IMTA salmon to the market. CBM considers not only the willingness to pay a higher price for the new variety of the product but also the ability of the consumer to adjust the quantities purchased of both the conventional variety and the IMTA variety of the salmon. Additionally, non-consumers of farmed salmon would derive environmental benefits from the adoption of IMTA of between

[4]In this context, WTP is the amount that an individual is willing to pay for a change in product attributes that improves welfare from the product's consumption (e.g. better quality and more sustainable production source).

CAD 43 and CAD 65 million per year over the same period, as revealed using data generated by the same survey. In the latter analysis, the benefits were derived by asking non-consumers of farmed salmon how much they would be willing to pay as subsidies to encourage salmon aquaculture producers to switch to IMTA (Martínez-Espiñeira *et al.*, 2016).

Production from IMTA systems, especially if combined with eco-certification labelling, could prove useful in increasing the desirability of Atlantic salmon and the likelihood that consumers choose the product. This finding has been confirmed by various studies that have looked at the utility derived from eco-labels for more sustainably produced foods (Wessells *et al.* 1999; Onyango *et al.*, 2005; Olesen *et al.* 2010). Producers and policymakers could consider the development of an eco-certification programme to differentiate and increase the attractiveness of sustainable products using methods such as IMTA. For example, IMTA kelps produced on the east coast of Canada by Cooke Aquaculture Inc. obtained organic certification according to the Canadian Organic Aquaculture Standards (Chopin *et al.* 2014). If price premiums are large enough, a portion could be used to cover the costs of certification programmes.

On a related point, social acceptance and consumer perceptions of IMTA are an important component of the discussion regarding the economics of IMTA. Public perception of the IMTA system and IMTA products is critical to the success of the system. Several studies have addressed these questions to date. Ridler *et al.* (2006) gauged public acceptance of IMTA in an attitudinal survey in Eastern Canada in 2003. Respondents had a positive opinion of salmon monoculture, largely due to its economic and employment impact. However, respondents indicated a greater approval for IMTA and also felt that IMTA would improve the public image of the aquaculture industry. A critical finding was that, while the principle of IMTA was attractive, there was limited knowledge of IMTA amongst respondents. Additionally, Shuve *et al.* (2009) conducted a survey of New York seafood consumers to determine consumer attitudes towards the IMTA system and IMTA products. The results of the study showed that 88% of the respondents supported the use of IMTA. Respondents felt that, compared with monoculture systems, IMTA was better for the environment and more considerate of animal welfare. IMTA seafood was also considered to be of equal or higher quality, freshness and taste compared with conventional seafood. Other studies have found similar results.

Barrington *et al.* (2010) addressed the lack of knowledge of IMTA by conducting a focus group study to determine whether a favourable impression of IMTA would be maintained once respondents were provided a detailed description of the system. Opinions on IMTA were gathered from restaurateurs, residents living near aquaculture operations and the general population after participants were provided with a description of IMTA. The authors found that all participants considered IMTA products safe to eat. Additionally, the authors concluded that 'people felt that IMTA had the potential to reduce the environmental impact of salmon farming, while improving waste management in aquaculture, creating employment opportunities, benefiting community economies, and improving industry competitiveness, food production, and the sustainability of aquaculture overall' (p. 206). The authors also found that participants seemed 'sceptical or unsure if IMTA could discourage disease outbreaks, replenish natural stocks, or improve food quality' (p. 206). They concluded that a promotional campaign would be helpful in educating the public on the benefits of IMTA.

Still considering the North American context, Yip *et al.* (2017) explored consumer preferences for Canadian farmed salmon in the US Pacific Northwest using IMTA in comparison with conventional net-pen technology and closed containment aquaculture (CCA). They investigated how salmon consumers perceive IMTA and other salmon aquaculture methods and what these consumers would be willing to pay for salmon produced by IMTA compared with potential substitute technologies (e.g. CCA). The researchers found that consumers have a more positive perception towards IMTA than CCA: 44.3% of the respondents preferred IMTA to conventional net-pen technology, whereas only 16.3% of the respondents preferred CCA. While the respondents perceived both methods as environmentally friendly, 70% of the respondents who chose IMTA felt that it was more 'natural' than CCA. Using the choice experiment valuation methodology, the study also revealed that consumers from the traditional markets for British Columbia farmed salmon were willing to pay a 9.8% premium for IMTA over conventionally produced Atlantic salmon.[5] On the other hand, the sample was only willing to pay a 3.9% premium for CCA over conventionally produced Atlantic salmon. Furthermore, with the introduction of IMTA and CCA salmon, 38.4% of the respondents indicated they would buy farmed salmon more frequently. Those who would buy more often would do so, on average, 5.87 additional times per year (median = 4). These results suggest that the presence of IMTA and CCA would have a non-trivial, but limited impact on the volume of consumer demand for salmon.

[5]A choice experiment is an attribute-based stated preference valuation method that is increasingly used in non-market valuation research involving the environment (Hanley *et al.* 1998).

Reviews in Aquaculture (2020) **12**, 1579–1594

Overall, the Yip *et al.* (2017) study revealed that the majority of salmon consumers were aware of the environmental concerns surrounding conventional salmon farming and 63.5% of them were supportive of adopting a more sustainable salmon farming method even if it is more expensive. Most importantly, the majority of salmon consumers were willing to pay a premium for reduced environmental impacts from the aquaculture industry. While IMTA and CCA both have environmental advantages and limitations, IMTA was a preferred option over CCA when both were presented and evaluated by salmon consumers at the same time. Such results may indicate that many consumers believe IMTA is more effective in reducing environmental impacts than CCA. However, the potential demand and estimated premiums associated with IMTA salmon cannot be realized without appropriate labelling and marketing by the industry.Finally, an increasing body of work outside North America is now emerging under the auspices of the European IDREEM project (Increasing Industrial Resource Efficiency in European Mariculture). In one study, Alexander *et al.* (2016a) carried out a series of stakeholder interviews (44 in-depth interviews in six countries) to ascertain potential concerns as well as possible benefits from the development of IMTA in Europe. Concerns mostly involved locational and food safety issues, while perceived benefits related to minimizing wastes and associated impacts as well as filtering of sea lice (notably absent in perceptions of IMTA in North America and still technically uncertain at commercial scale). While these issues were commonly expressed across the six countries, the emphasis on each varied. A second study considered public opinions towards IMTA in five European countries, in contrast to stakeholder views (Alexander *et al.* 2016b). Findings from a large survey (2520 respondents) indicated that public perceptions and social acceptability towards IMTA in Europe are similar to what has been demonstrated in North America; there is a mixed view of aquaculture generally and a lack of awareness of IMTA and integrated aquaculture methods. The authors conclude that raising awareness of the potential role of IMTA is needed before IMTA is likely to gain wider acceptance. Finally, van Osch *et al.* (2017) estimated Irish salmon consumers' WTP for IMTA salmon, again using the choice experiment method (see Yip *et al.* 2017). Energy rating labels were used as an eco-label to illustrate the environmental pressures from salmon farming to respondents. As with earlier studies cited above, this study demonstrated that the Irish public is willing to pay a price premium for sustainably produced farmed salmon.

Based on the growing stakeholder and market research completed to date in North America and Europe, public attitudes towards IMTA appear to be positive, but more effort is needed to advance public awareness of integrated aquaculture techniques.

Closing the gaps: advancing the economic analysis of IMTA

In this section, we examine the prospects for increased economic and financial analysis of IMTA systems. We concentrate on the directions that, in our estimation, future research should pursue. We begin with a discussion of the potential approaches for integrated ecological and economic modelling of IMTA systems. Then, we examine the development of more instructive analyses involving IMTA system profitability, including its relationship with (species) ecological efficiency, and the use of economic incentives to foster socially desirable aquaculture system expansion. Finally, we consider the need for advances in analysing markets and consumer/social acceptability of IMTA systems, including an expanded role for WTP studies but with the use of more advanced methodologies.

Bioeconomic modelling of IMTA

Interesting economic questions arise with the analysis of more sustainable forms of aquaculture. What are the net economic benefits of such operations, and how are these formulated vis-à-vis conventional aquaculture operations? How do we properly model an IMTA operation as an integrated system when by 'integrated' we mean biological/ecological and economic/societal? As our earlier review of the current research revealed, these questions have not been addressed conclusively to date. Here, we explore the potential of bioeconomic models to address at least some of these questions. We formulate a standard bioeconomic model that could be used in a comparative analysis of IMTA and conventional aquaculture operations, to illustrate the approach. Since this is a conceptual model, we provide a few details of the underlying management complexity of IMTA systems before describing our simple model, leaving details of the stylized model to an appendix (Appendix). We then show how this modelling exercise can serve as the starting point for a series of extensions and derivations to explore some of the key questions introduced elsewhere in this paper.

Formulating the bioeconomic model requires consideration of the potential nutrient streams generated by an aquaculture system. Nutrient waste from the fed component in an aquaculture system can be partitioned into three categories, consisting of dissolved inorganic nutrients (soluble inorganic end products of metabolism and respiration) and organic particles (faeces and waste feed) partitioned into smaller suspended particles and heavier settle-able particles. Extractive species can be grouped into three different niches corresponding to each of the abovementioned 'nutrient streams'. In many cases, IMTA is practised with seaweeds and shellfish representing the first two of these niches. While there has been experimental work with deposit feeders, such as sea urchins and sea cucumbers (Cubillo *et al.* 2016; Carras *et al.* 2019; Zamora *et al.* 2016), the development of component species for this niche is ongoing. For now, we subsume the various complexities of modelling distinct niches in our bioeconomic model into a single finfish species and a single extractive species.

In the appendix, we formulate the management problem as one of maximizing the net economic benefits of a representative aquaculture operation and describe a basic bioeconomic model that captures the main elements of the problem (Asche & Bjorndal 2011). The resulting optimization problem can be solved using optimal control and the maximum principle for a conventional finfish farming operation (e.g. salmon farm) and an IMTA operation (e.g. salmon plus extractive species). This approach allows for a comparison of the net economic benefits and operational results for the two farm types. However, a more complete (and complex) analysis might include the combination of a standalone finfish farm and standalone extractive species farm for comparison to the IMTA operation. In effect, this approach allows for consideration of the distinct cases where adopting IMTA provides incremental production/supply of the extractive species to the market (finfish farm only as comparator), or where it does not increase production of the extractive species and instead simply repositions otherwise standalone operations (individual finfish and extractive species farms). This distinction is important, since the former case primarily has implications for markets and perhaps prices because the extractive component represents entirely incremental production. In contrast, the 'repositioning' case instead reduces the aesthetic and ecological 'footprint' of separate standalone operations appreciably, but perhaps has relatively little impact on the volume of production.

Extensions of the model could include determining optimal effluent taxes on farm wastes under conventional versus IMTA technology and assessing the effects of various restrictions such as limited site area, a regulatory standard under either technology or the potential for a 'nutrient credit'. While no published research has demonstrated this full suite of analyses to date, clearly there is an enormous opportunity for interdisciplinary research.

Bioeconomic models might be useful not only for regulators but also for aquaculture operators to assist them with translating their various data into useful and quantitative information for farm management. This is particularly true for IMTA systems where the non-linear relationships between the different components of production could be simulated and integrated into simple decision support tools to aid farm operation.

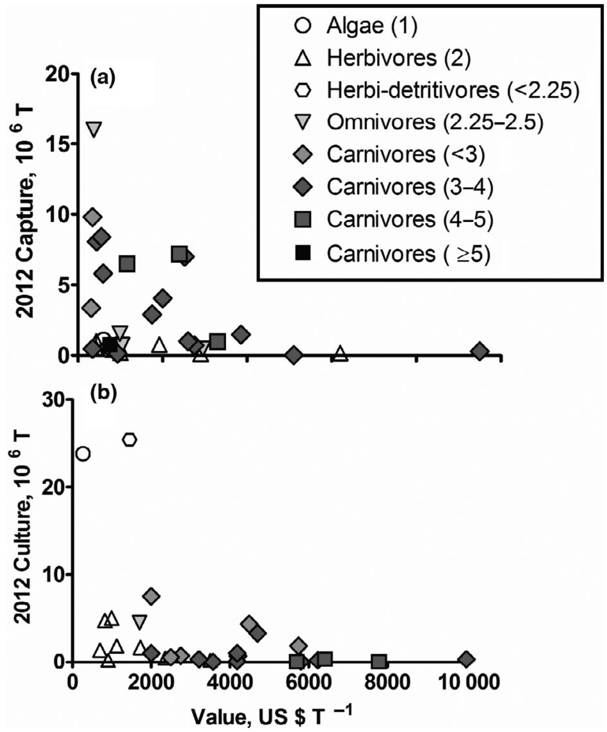

Figure 1 Plot of trophic level (TL) as a function of production and unit value for the top 25 species in 2012, globally, for (a) capture fisheries and (b) aquaculture. Numbers in parentheses in the legend are typical trophic-level values for the group (Data from FAO FIGIS 2014).

Ecological efficiency, private incentives and adoption of IMTA

Capture fisheries produce mostly carnivorous animals, while aquaculture produces mostly species that are closer to the base of the food pyramid (Neori & Nobre 2012; Fig. 1). These aquaculture species also command a lower market value per kg than other species. Is the combination of a low trophic level and low price merely a coincidence? How can it be understood? What does it imply for a seafood market that is dominated by cultured species (FAO 2016)? What are the implications for IMTA, where different trophic levels are integrated into a single operation? Here, we synthesize the main ideas from Neori and Nobre (2012), who examine the importance of trophic level and ecological efficiency in relation to other considerations (e.g. consumer preferences, traditions and technology) in the determination of profitability and scale of production of aquatic species, with special reference to IMTA.[6]

Ecological efficiency does not seem to be directly relevant to cost in capture fisheries. However, in aquaculture it directly determines the costs of feed and waste treatment,

[6]Ecological efficiency can be defined as the efficiency of energy transfer from resources, through the trophic levels, to products.

which are two of the main production expenses. Waste also limits yield through its impact on water quality, which often determines the success or failure of any fish farming operation (Swann 1997). The cultured species that are close to the base of the food chain pyramid often use aquatic food resources more efficiently and produce less waste than cultured predators. Most of aquaculture's leading organisms – 'green water' phytoplankton (food for filter feeders), filter feeder fish, seaweeds and bivalves – are *extractive* species, that is unfed organisms that extract their nutrition from the water column, cleaning the water column in the process. About half of world aquaculture production (fresh weight) in 2014 is represented by this group of organisms (FAO 2016). Carnivores are *fed* species; that is, they cannot be cultured on 'natural food'. They must be fed a rich feed and discharge a significant proportion of the nutrients they consume to the water as they grow. This is likely the reason why the culture of salmon, the leading cultured aquatic carnivore, is at least twice as expensive per kg as the production of kelps, carps and bivalves.

Expensive production technologies, with negative impacts on the environment and society, can result in a 'high-value' fish being priced out of the mainstream seafood market. In contrast, it seems that low trophic-level organisms are more profitable, even though their revenue per kg is low, due to their low production cost and the large demand for affordable seafood. By encouraging the culture of such species, IMTA can improve the ecological efficiency of the aquaculture operation, cut production cost and increase sustainability (Neori & Nobre 2012; Zhang *et al.* 2015). A recent study of the huge Chinese aquaculture industry has identified a shift from environmentally damaging to ecological remediating practices (Zhang 2014). As a consequence, IMTA farms can be more profitable to their owners than monoculture farms, as discussed above. For example, basic farm blueprints and financial analyses have suggested that seaweed farms on land can be profitable, particularly when integrated with the farming of fish or shrimp, because of the savings on seaweed fertilization and on wastewater treatment, and bio-diversification (Neori *et al.* 2004). Shpigel and Neori (1996) evaluated three hypothetical designs for the integrated culture of molluscs with algae and fish in land-based mariculture facilities and made rudimentary cost-analysis predictions. Under the conditions prevailing in Eilat, Israel, the analysis predicted significant prospects for profitability for all three designs. However, two farms that sprung up several years later based on two of these designs did not reach profitability, likely because of their small and, therefore, uneconomic size. Nevertheless, one of these designs supplied a conceptual basis for several profitable abalone-seaweed farms in South Africa (Robertson-Andersson 2007). In contrast, much of the literature reviewed earlier examined a fixed configuration for an IMTA operation in affluent regions (and for any other systems used for comparison). Yet it seems obvious that for profitability analysis to be truly useful, it will be more helpful if such analyses consider, using mathematical models, various options in the system configuration, including the mix of species, feeding regimes, scale and location, and seek to identify the optimal system design.[7] Such analyses can have several benefits. For example, by identifying optimal design characteristics the prospects for adoption of IMTA should improve in tandem with enhanced profitability. Additionally, by analysing and identifying important components that can improve system performance and profitability, suitable incentives can be formulated where the integration of these improvements is hindered in some way.

It also should be recognized that financial analyses of IMTA systems need to acknowledge substantial differences between affluent versus poor regions when studying IMTA performance, as the type of systems and the costs involved may differ greatly and comparisons across regions may be misleading. In this light, comparative analyses involving IMTA are important too. Alternative technologies, such as closed containment, may appear to present greater profits or be more appealing, often with no economic substantiation (Hargreaves 2016). As a result, performing comparative analysis of IMTA and competing technologies may be more instructive than standalone analysis of IMTA in isolation, as demonstrated by the Yip *et al.* (2017) study cited earlier.

The adoption of the IMTA concept by industry in Western countries has lagged behind the scientific and technological developments of the concept.[8] Much of the groundwork on land-based IMTA was published in the early 1970s (see Ryther *et al.* 1975). The economic and environmental advantages of IMTA farms have led to a slow but evident increase in their deployment worldwide, most notably in China (Troell 2008; Buschmann *et al.* 2009; Troell 2009; Xiang 2015). Still, proper financial analyses are lacking. In China, open-water IMTA operates at the scale of whole bays (Xiang 2015). For example, in Sanggou Bay, described earlier, scallops are cultivated together with kelps, abalone and fish, in cultures extending 18 km offshore (Ferreira *et al.* 2008; Shi *et al.* 2013). Another open-water IMTA system of kelps with salmon and mussels operated in the Bay of Fundy, Canada (Chopin *et al.* 2012).

[7]The bioeconomic modelling formulation described in the previous section is a step in this direction, but of course, using more sophisticated computing facilities and model formulations would allow for optimization analysis on a larger scale as suggested here.

[8]Various authors have discussed the main obstacles that have slowed down adoption of the IMTA concept by the industry in the Western world (see Troell *et al.* 2003; Troell *et al.* 2009; Hughes and Kelly ; Granada *et al.* 2015; Chopin 2017, 2018, 2019).

Abalone-seaweed farming in South Africa is another example of an IMTA system operating on land. IMTA's advantages compared with monocultures are in the realms of environment (e.g. reduced impact), society (e.g. more jobs and reduced use of capture-based feeds) and marine ecosystems (e.g. reduced harvest of natural beds of seaweeds and small fish helps maintain coastal biodiversity).

As such, profitability alone should not be the single consideration in promoting the adoption of IMTA, as noted earlier. Governments can help entrepreneurs overcome the aforementioned obstacles by the provision of financial incentives, which provide recognition for the value of the IMTA operation in addressing unpriced external costs. A system of incentives may be more effective than laws, rules and regulations in the encouragement of responsible and sustainable aquaculture in general (FAO 2006), and IMTA in particular. Future government policies that create incentives for IMTA adoption need to use different approaches depending on the social reality. Industry structure clearly needs to be recognized, that is larger, concentrated operations with a mass-production and monocropping focus in Western countries versus smaller-scale, smallholder regimes in less-developed, tropical regions. In the latter countries, services provided to the small farmer by the multi-trophic operation of the farm, in the form of waste reduction, water recycling, product diversity, food security and unskilled jobs, may make the approach attractive, provided that the technical and capital issues are resolved. This is probably why IMTA farms are so dominant in such countries, primarily in freshwater, and in a less structured form in seawater. In Western countries, the bottom line of the farm matters most. The external benefits of IMTA farms, in the form of nutrient capture (biomitigation) and water recycling, must have a monetary expression if they are to influence and encourage IMTA farm adoption in these countries. Being a new concept, compared with Asian polyculture and with modern shrimp and fish monoculture, IMTA farms require public support, guaranteed loans and subsidies to attract private entrepreneurs and investment to take what is perceived as a large risk.

Clearly, proposals for systems of incentives to promote IMTA based on the rate of internalization of a number of aquaculture externalities are attractive. One such alternative is the use of 'nutrient credits', wherein the reduction or biomitigation of nutrients in comparison with competing conventional aquaculture technologies is rewarded via the assignment (or payment) of credits linked to the reduction in nutrient loads compared with equivalent monoculture systems (Chopin *et al.* 2010). While its application is complex, some insights are available from the design and implementation of existing nutrient trading schemes. An example of such a programme is the Chesapeake Bay Nutrient Credit Trading scheme adopted by some of the surrounding States (Van Houtven *et al.* 2012).[9] However, despite the general support for such schemes and its promotion by the U.S. Environmental Protection Agency, very few trading schemes have been implemented in the USA (King & Kuch 2003).

Besides the abovementioned incentives, governments can reduce the initial investment, operational costs and perceived risks involved with IMTA farms with the creation of IMTA parks. In these parks, and also outside them, IMTA entrepreneurs could be offered suitable space and government-backed credit at attractive conditions. The benefit from these demonstration and training centres could include help in planning and engineering, provision of affordable and ongoing technical help, such as extension services, grants and loans, subsidized supply of seed for the different organisms and, finally, assistance in the marketing of the different products. Facilities that can educate and train operators are also essential, in the form of specialized curricula at existing institutions, the establishment of new ones and the establishment of effective extension services, which can provide real-time support and advice to farmers. There is a growing awareness that environmentally sensitive aquaculture makes good business sense and helps poor and small-scale farmers (FAO 2006). This awareness can be harnessed in the education of farmers about the benefits that IMTA can have for profits, and in the education of the consumers and policymakers about the advantages of IMTA products.

Markets, prices and eco-labelling

As sustainability and green markets become more popular around the globe, businesses and researchers increasingly are interested in estimating the value society places on improving environmental products and services. WTP-type studies began in marketing research with the primary focus of determining the best pricing strategy to maximize profits for sellers. More recently, WTP studies of environmental products and their attributes can target IMTA products and assist producers and policymakers in a variety of ways, such as locating market niches (Chern *et al.* 2002), raising producer and seller confidence in greener products (Aguilar

[9]There are other complexities to consider. From a purely economic efficiency perspective, it is more appropriate to tax the externalities created by all producers engaged in producing the same product with a similar rate per unit of waste. This induces operators to adopt less polluting technologies (e.g. IMTA) to save on the pollution charge or tax. Both monocultures and IMTA operations would be taxed, but the latter would pay a lower total tax, more or less equal to the nutrient credit discussed in the text. Moreover, not all nutrients are necessarily bad, as was pointed out in an earlier footnote. In the end, regulators are not likely to have the information needed to design optimal taxes, but may know the ecosystem carrying capacity, favouring a nutrient trading scheme for those situations where nutrients are causing damages.

& Vlosky 2007; Liljenstolpe 2008), helping producers price their new products more accurately (Kannan *et al.* 2008), providing the basis for public policy recommendations (Roe *et al.* 2001; Onyango *et al.* 2005; Goddard *et al.* 2007) and understanding consumers' attitudes towards environmental improvements.

Many WTP studies exploit the complementarity of the food product and the public benefit to estimate the monetary value of the latter. This strategy has been followed by several researchers interested in estimating WTP values for analogous attributes of seafood (Wessells & Anderson 1995; Jaffry *et al.* 2004). For example, the WTP for eco-labelled seafood, safer seafood, non-GM seafood and organic seafood has been the focus of previous works. However, most of these studies use a relatively simple payment question, such as 'Would you be willing to pay a 15% premium for [the product or variety of interest] as compared to [the conventional counterpart]?' or 'Would you be willing to pay a $X premium for the [product or variety of interest] as compared to [the convention counterpart]?' Of course, the size of the premium would be varied across survey respondents following the usual strategy found in dichotomous choice CVM studies. However, one must account for the fact that with the adoption of IMTA seafood prices could vary and the quantity of seafood purchased in the future may change as well (Corsi 2007).

Analysis of WTP and determination of possible price premiums for IMTA products face various additional challenges. For example, a typical CVM study addresses the case of an exogenously imposed quantity or quality change, but this would not work in the case of an impure public good, such as occurs with a pro-environment change in a food product.[10] For this reason, one must trace the demand curves for salmon consumption with and without IMTA adoption in a contingent behaviour questionnaire (Whitehead *et al.* 2003; Huang *et al.* 2004; Martínez-Espiñeira *et al.* 2015). Researchers must first determine the amount respondents currently consume at a baseline price, and the amount they are willing to consume with a (randomly assigned) price increase to set the baseline demand curve in the current market without IMTA. Further, the same questions must be repeated to trace the demand curve for a hypothetical market with IMTA. Such a task is further complicated when researchers try to imitate a real market choice situation by allowing respondents to express a choice between IMTA and conventionally farmed seafood, or even some combinations of both. In order to simplify this complex set of questions, it is often assumed that consumers will keep on buying the same quantity once the new product becomes available (Johnston *et al.* 2001; Johnston & Roheim 2006). However, Corsi (2007) pointed out that this would constrain artificially the consumers' choice and bias the welfare estimate resulting from the study.

As a result of the concerns raised above, choice behaviour and contingent behaviour techniques are being used, as the ability to predict actual choice behaviour is far greater with these techniques. For example, Martínez-Espiñeira *et al.* (2015) used a contingent behaviour approach and panel count data methods to analyse purchases of farmed salmon by consumers. Survey respondents were asked to indicate their expected purchases when different hypothetical prices for farmed salmon were presented to them (before IMTA salmon is available and afterwards). This study also allowed for the realistic possibility that many consumers would switch only partially to the IMTA variety of salmon. It showed that most of the premium that consumers say they would pay for IMTA salmon is a result of IMTA salmon's conventionally farmed counterpart becoming the inferior option for the typical buyer. That is, all else constant, the demand for IMTA salmon would increase with increasing household income, which occurs with a 'normal good', and the demand for its conventional counterpart would decrease with increased household income, which is consistent with an 'inferior good'.

Certainly, the valuation of IMTA products can benefit from an understanding of the theory of product attributes. An attribute is relevant if the demand for a product is affected when there is a change in the nature of or information about that product attribute. Food products are endowed with a set of attributes that can be categorized as *search* attributes, *experience* attributes and *credence* attributes (Nelson 1970; Wessells 2002). With search attributes, the consumer can examine characteristics such as price, size, feel and colour, before purchasing the product. Thus, the consumer enjoys the availability of full information before committing to a certain purchase. However, experience attributes can only be ascertained after a product is bought and consumed. In this case, full information is not available to the consumer before the product is purchased as with a bottle of wine or a particular film. Partial information can be obtained from 'entrepreneurs' who will provide that information for a price (e.g. food critics, movie critics and consumer report magazines), so that consumers can save themselves the trouble of having to first purchase it in order to experience the good or service. In the case of salmon, a search attribute might be its flesh colour and an experience attribute might be its taste. Finally, in the case of credence (or post experience) attributes, the consumer cannot determine or observe a product's attributes either at

[10]An impure public good is a type of hybrid good that has features of both public and private goods (Cornes and Sandler 1984). Producing more sustainable seafood is an example because the seafood produced is consumed by individuals (private good), but the environmental benefits generated from production are shared by all (public good).

the point of sale or after consumption.[11] In this case, it is very costly to obtain information about the good or service and either governmental agencies or highly specialized external certification bodies are needed to provide information. Pharmaceutical products and medical treatments are examples of credence goods. Credence could be an important element in the marketing of IMTA products.

Many WTP studies have examined the price premium that consumers are willing to pay for 'greener' foods that provide some assurance of minimum social and/or environmental stewardship standards, which is a type of credence attribute. Usually, the issue is whether consumers will be willing to pay a premium large enough to cover the higher cost of the eco-labelled product and, in addition, the cost of the eco-labelling (certification) itself. In the case of IMTA products, where the products may be more profitable for producers than conventional products, this is less of an issue. As discussed above, primarily small focus group and attitudinal studies have been used to estimate the WTP for IMTA products until recently (Ridler *et al.* 2006; Barrington *et al.* 2010). Although the limited attitudinal studies show that consumers generally have positive perceptions of IMTA products, a gap has existed in the literature until fairly recently as to the amount consumers are willing to pay for IMTA products and their perceptions of IMTA products, thus hindering further research on the economics and profitability of IMTA. Consequently, future research must continue to fill this gap by using appropriate methods that are able to estimate the WTP for a hypothetical product, offer flexibility in price variations of the studied product and substitutes, and estimate the WTP for multiple attributes in a product.

Conclusions

With their obvious economic benefits as described here, the prevalence of IMTA systems in future may rise, perhaps even rapidly, as monoculture expansion slows due to input costs (e.g. feed, energy and medicines), environmental issues (e.g. waste and deteriorating water quality) and socio-economic concerns (e.g. public opposition). Moreover, our view is that successful diffusion of IMTA in the future may be best realized within an integrated coastal area management (ICAM) approach and beyond a restricted focus on existing finfish farm sites in isolation. Despite the various positive attributes of IMTA, research on its economics is still more or less in its infancy. To date, research on the economics of IMTA has focussed on three main areas: (i) economic studies that consider environmental externalities; (ii) financial analyses that address on-site profitability; and (iii) market analyses that look at public and consumer perceptions and the acceptability of IMTA systems, together with the WTP for IMTA products. Furthermore, scientific literature on the economics of IMTA has focussed predominantly on the financial side, which is a critical piece of the puzzle but one that ignores the full range of societal benefits associated with IMTA. Given the potential environmental benefits of IMTA compared with monoculture, additional economic analyses, which take into account positive and negative externalities associated with production, are needed to demonstrate the true value of IMTA to society.

[11]For example, the amount of a certain nutrient such as folic acid in a particular product cannot practically be determined by a consumer either before or after the product is bought and consumed, without proper labelling. This example illustrates that even if one allows for repeat purchases, a credence attribute cannot be transformed into an experience attribute.

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Appendix

In what follows, we take the simpler case of a comparison between conventional finfish aquaculture and IMTA operations. First, we develop the ecological component of the aquaculture system at time t, which describes the population dynamics for the finfish species S, with or without the extractive (biomitigating) species X, both denominated in biomass terms. We describe changes in the waste concentration W in the ambient environment (measured as a concentration or stock of waste) as the equation of motion, dW/dt. For simplicity, we assume there is no symbiosis between species, but this could be incorporated if there is evidence to support it. For the conventional standalone finfish farm, the necessary equations are as follows:

$$\frac{dS}{dt} = f(S(t)) = (\alpha_0 - \alpha_1 S(t))S(t)$$
$$\frac{dW}{dt} = aS(t) - cW(t) \tag{1}$$

where the first equation describes growth of the finfish biomass (no biomitigation component) and α_0 and α_1 are the parameters of an inverted U-shaped growth function, and the second equation describes the evolution of the waste concentration where a is a parameter describing the contribution from the finfish and c is a parameter expressing the assimilative capability of the ambient environment.

For the IMTA system, we introduce an additional equation of motion describing the growth of the extractive species, which is interdependent with the finfish component. It is also necessary to modify the equation of motion expressing the evolution of the waste stock since it now includes a biomitigation element. As a result, the ecological relationships describing the IMTA system are as follows:

$$\frac{dS}{dt} = f(S(t)) = (\alpha_0 - \alpha_1 S(t))S(t)$$
$$\frac{dX}{dt} = g(X(t), S(t)) = (\beta_0 - \beta_1 X(t) + \beta_2 S(t))X(t) \tag{2}$$
$$\frac{dW}{dt} = aS(t) - bX(t) - cW(t)$$

where the first equation is as before and the second describes biomass growth of the extractive species, with parameters β_0, β_1 and β_2. Note the interaction term in this equation, $\beta_2 S(t)X(t)$, which indicates that a larger biomass of the finfish species leads to a larger extractive species biomass. Finally, the last equation includes the term $bX(t)$, which allows for the biomitigation of wastes by the extractive species, with parameter b showing this process as a function of the extractive species biomass, X.

Next, we consider the economic component of the system comprising the damage or loss functions describing how externalities created by an aquaculture operation affect human welfare. We consider two externality groupings. The first refers to the waste stream produced by the operation and discharged into the ambient environment; as described above, this external effect can be at least partially biomitigated using an appropriate extractive species. We represent this damage function as $D(W(t))$, with $D_W > 0$, as clearly an increase in wastes results in larger damages. A second source of external cost from the operation is a mix of aesthetic losses, foregone (or recovered) ocean space that is assumed to have some opportunity cost, as well as issues of safety and access arising from the presence of open-water facilities in an area used by recreationists, for example.

Finally, we can formulate the optimization problem that brings all the various components together within a standard dynamic bioeconomic framework. The objective is to maximize social welfare π, composed of revenues from production (with or without the extractive species X), less the production costs, either $C(S(t))$ or $C(S(t),X(t))$, and less the damage costs from wastes, $D(W(t))$.[12] Social welfare is maximized subject to the ecological system components described above. Assuming the farm capacity is preconfigured, and then, the variable subject to adjustment or control could be the timing of the production cycle T. Taking this approach, we can express the optimization problem for the IMTA operation as follows:

$$\max_T \ \pi = \int_{t=1}^{T} \{(p_S+\eta)S(T) + (p_X+\mu)X(T) - C(X(t),S(t)) - D(W(t))\}$$
$$\text{Subject to:} \tag{3}$$
$$\frac{dS}{dt} = f(S(t))$$
$$\frac{dX}{dt} = g(X(t),S(t))$$
$$\frac{dW}{dt} = aS(t) - bX(t) - cW(t)$$

where p_s and η are the finfish price and IMTA price premium (if applicable), respectively, and p_x and μ are the price and IMTA price premium for the extractive species.[13] Defined this way the problem has similarities to an optimal timber rotation analysis in the forest industry where T is the optimal rotation length, but the problem could also be formulated in terms of maximizing social welfare over a constrained farm area or production capacity.[14] Additionally, a discounting procedure can be added to account for the time value of funds and if the comparison involves a switch from monoculture to IMTA then the added costs of switching should be included in (3).

Solving the model in (3) yields the optimal length of the production cycle and optimal values for all other variables. Once determined these values can be inserted into the objective function in (3) to give the maximized value of social welfare from the operation in question.

[12]However, note that mild nutrient enrichment could be positive where nutrient limitations restrict primary production. In such cases, moderate waste production is not necessarily 'damage', as indicated here. To capture such complexities requires a more complex specification of the damage (or enhancement) process. For the purposes here, we assume that the marine system is sensitive to nutrient loadings in a negative way.

[13]Only the integrated operation formulation is shown here due to space constraints but the conventional finfish operation would look similar except that the extractive species X would be removed, and there is no price premium.

[14]See Asche and Bjorndal (2011) for a full elaboration of an aquaculture management problem formulated in optimal rotation terms.