Integrated Multi-Trophic Aquaculture

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The purpose of this paper is to inform the SARF Board of the current status of IMTA as it might apply in a Scottish context, with a view to identifying opportunities, barriers and possible research requirements. It is not intended as a comprehensive review of the entirety of the integrated aquaculture debate. Comprehensive reviews can be found elsewhere [1].

The report covers

- *a brief review of existing IMTA in countries with equivalent conditions and aquaculture sectors*
- *technical, economic, environmental and regulatory issues (in a Scottish/UK context)*
- *identification of knowledge gaps and recommendations for further applied R&D/demonstrations*

Integrated aquaculture has two principle objectives: to reduce pollution and to increase productivity. Despite these aims being in line with industry drivers and a wealth of scientific evidence that at an experimental level integrated aquaculture meets these objectives, there has been very limited industry development. The authors are only aware of a single company commercially producing salmon and other products in an integrated aquaculture operation. This company is based in the Bay of Fundy, Canada. In a Scottish context there have been a number of experimental/pilot scale trials which have yielded encouraging scientific results, but as yet there is no major commercialisation.

A number of key constraints have been identified as reasons for this lack of acceptance by the aquaculture industry:

Economic: There is a lack of hard economic analysis of integrated aquaculture. Two economic simulations have shown that integrated aquaculture has the potential to yield increased profitability and resilience to the business.

Regulatory: In Scotland there is no regulatory barrier to integrated aquaculture

Bio-security: Concerns about co-culturing multiple species has been raised as a constraint on the development of integrated aquaculture. Studies have shown the interaction between co-cultured bivalves and infectious agents of salmon varies with infectious agents

- Infectious salmon anaemia virus: Mussels are not a reservoir or vector of this virus and may deactivate them through ingestion.
- *Vibrio anguillarum*: Mussels accumulated the bacteria in their gut and faeces and may act as a disease reservoir
- Infectious Pancreatic Necrosis virus (IPNV): There is a lack of clear scientific study but there is evidence that mussels uptake the virus and shed them in their faeces
- *Lepeophtheirus salmonis:* Mussels have been shown to uptake early life stages, and may act as a control on the sea lice population.

It is worth noting that in open cage aquaculture there has always been a degree of co-culture with biofouling and natural communities in the sea cage environment. There has been little evidence of accumulation of therapeutants, heavy metal or persistent organic pollutants in the co-cultured products.

Of these it is probably the economic constraint where there is the most need for further research to prove the business case for integrated aquaculture.

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Integrated Aquaculture in Scotland

Current State of Industry

The authors are unaware of any current commercial integrated aquaculture systems in operation in Scotland. A number of smaller operations are running experimental/pilot scale operations (Loch Duart Ltd, West Minch Salmon Ltd, Muckairn Mussels).

Current State of Research

Sea urchins and Atlantic salmon [3-5]

The research on sea urchins has shown conclusively that a direct trophic linkage exists between the urchins and salmon feed, provided the sea urchins are appropriately situated within the trajectory of feed waste, are gaining shelter from the salmon cages and are housed in cages of the correct mesh size. In economic terms this offers advantages in so far as the urchins need no additional feed for the duration of the grow out cycle which for these species at local sea temperatures would be approximately 2 years. Operationally however the sea urchin cages, if in sufficient numbers, are likely to present a real obstacle to normal husbandry routines for salmon (boat access, net changes, bath treatments etc.) and therefore engineering design and incentive is required to assist this process. In the trial the sea urchins were situated outside the salmon cage nets and they were undoubtedly serving to reduce the amount of salmon feed that would otherwise fall to the sea floor and contribute to its organic enrichment. However as salmon feed supply systems become more and more sophisticated, there is less waste feed and this will clearly limit the number of sea urchins which can be supported in any given location around the cages.

The co-culture of sea urchins and salmon has potential provided the engineering and logistical aspects of this process can be progressed. The use of urchins is likely to hold greatest appeal to firms operating in niche markets, or seeking a way to heighten their ‘green’ credentials. To overcome the operational impediment of sea urchin cages attached directly to salmon cages, the growers might opt to farm seaweeds as additional sea urchin feed, the associated sea urchin operation then being at some distance from the salmon cages. In this system the urchins would act as indirect bioremediators, their consumption of seaweed resulting in a net reduction of (dissolved) nitrogen from the ‘farmed’ water body.

Macroalgae and Atlantic Salmon [6, 7]

The culturing of seaweeds adjacent to caged salmon shows that seaweeds can benefit from the additional farm-origin nutrient supply in mid to late summer when available sunlight is high and ambient nutrient levels are falling. However, it is also evident that other physical parameters, particularly current speed and depth (on account of light attenuation), also influence growth. There is evidence that in some of the trial locations the seaweeds are benefiting from higher current speeds to the extent that this outweighed any measurable advantage of additional nitrogen.

Seaweeds cultured very close to salmon cages and where current speeds are low can become coated in the finer components of fish feed and faeces which inhibits their growth and potentially product quality. The condition of the cultured fronds is obviously of greater relevance where the purpose is to achieve a viable crop for resale rather that culture purely for bioremediation purposes.

At maximal extrapolated yields, a hectare of *Palmaria palmata* may absorb as much as 30% of the nitrogen output from a 500 tonne salmon farm (total harvest 340 tonnes wet weight (wwt) ha-1, *P. palmata*, containing 7% dwt nitrogen). More conservative estimates are in the range of 12 % (total harvest 180 tonnes wwt ha-1, 5.5 % dwt nitrogen). *Saccharina latissima* might absorb as much as 10 % (total harvest 340 tonnes wwt ha-1 , S. latissima 3% dwt nitrogen) but more conservative estimates are around 5.3 % (total harvest 220 tonnes wwt ha-1, 2.5 % dwt nitrogen).

While it may be desirable to demonstrate an uptake and removal of nutrients (by harvest of seaweed) at a co-culture farm scale, the true 'buffering' of eutrophication may occur at much broader geographic scales and hence direct utilisation of fish farm origin ammonium may be less important that managing coastal nitrogen budgets. In other words the aims of integrated aquaculture may be met by extractive and enriching forms of aquaculture sharing the same water body rather than being in direct proximity.

Oysters and Atlantic Salmon [7]

Pacific oysters (*Crassostrea gigas*) were cultured in the stream of waste particulates from farmed Atlantic salmon. Growth patterns suggested the particles were not always utilised as a food source; presumably their requirements were being met by ambient seston for the majority of time.

Conclusions from Scottish Research
Research has shown a direct nutrient transfer between salmon farm wastes (particulate and dissolved) and sea urchins and seaweed can be achieved when they are co-cultured.
Well-designed integrated systems can lead to a reduction in nitrogen emissions from caged fish through harvest of sea urchins and seaweeds. However, for cultured bivalves, greater success in demonstrating a link to fish culture may occur where ambient phytoplankton or seston is limiting.
For integrated systems of fish, filter-feeding or grazing invertebrates and seaweed, the influence of background environmental characteristics must be seen as primary design considerations.
To make significant impacts on dissolved nutrients emanating from fish farms, large quantities of seaweed would have to be grown.

Integrated Aquaculture in Canada

Current State of Industry

On January 27 2011 Loblaw (Canada's largest food distributor and largest buyer and seller of seafood) announced that it would start selling WiseSource™ Salmon. This salmon is being produced by True North Salmon Company using Integrated Multi-Trophic Aquaculture.

Current State of Research

Most Canadian research is based on the Atlantic Coast, in the Bay of Fundy where research began in 2001. The research is currently concentrating on an integrated system of salmon (*Salmo salar*), blue mussels (*Mytilus edulis*) and kelps (*Saccharina latissima*). Increased growth rates of kelp species of 40-50% [8] and mussel size by 15% [9] have been reported as a result of integration. There are also experimental scale integrated aquaculture trials on the west coast where shellfish (mussels, oysters and scallops), kelps (*Saccharina latissima*), sea cucumbers, and sea urchins are being co-cultured with salmon and sablefish. In addition work on consumer acceptance and biosecurity have been undertaken and are detailed below.

Integrated Aquaculture in Chile

Although much of Chilean integrated aquaculture is land based, the co-culture of blue mussels around open water salmon pens has become common. The placement of the mussel ropes is driven by availability of space as opposed to optimal design. However the mussels are increasing the profitability of the industry while reducing its environmental impact [10]. This is a rare example of the driver for integration coming from industry rather than being research led. In addition open water macroalgal cultivation is being trialled, with growth rates being 30% higher in integrated systems[11], and it has been calculated that a 100 ha *Gracilaria* (macroalgae) long-line system will effectively reduce the nitrogen inputs of a 1500 tonnes salmon farm [12].

Issues of Special Interest

Regulation [7]

The Scottish Executive (1999) 'Advice note: marine and fish farming and the environment' stated that the indicative distance between a fin-fish farm and a shellfish farm should be a minimum of 3km. However the Town and Country Planning (Marine fish Farming) (Scotland) Order 2007 has superseded these regulations. There is currently no legal barrier to licensing of integrated aquaculture operations in Scotland and several licences have already been granted. However due to novelty of these applications the regulation may not provide a 'good fit' for integrated operations and the complexity of the process will be determined by any consents already in place. A new integrated system could potentially need both planning and discharge consents, and depending on the scale of the operation, an EIA. It is worth noting that currently seaweed production falls outside the planning systems. The issue of scale of surface-floating infrastructure will be relevant in terms of visual impact, access to other users, and safety of navigation.

Research and Innovation Recommendations
In conjunction with statutory and regulatory bodies, produce comprehensive step by step guidelines to applying and gaining consents for integrated aquaculture sites and production.

Economics

Full and comprehensive economic analysis of integrated aquaculture is difficult to find. There are two principle studies, both simulations, one based on the west coast of Scotland and the other in the Bay of Fundy Canada. In a simulation of a salmon-mussel system (nominally on the west coast of Scotland) it was shown that there is a definitive economic benefit from integration [2]. The value of this integration is dependent on the increased productivity of mussels grown in combination with caged salmon (see figure 1). However the study revealed that a fall of 2% pa in the price of salmon offsets any benefits of integration.

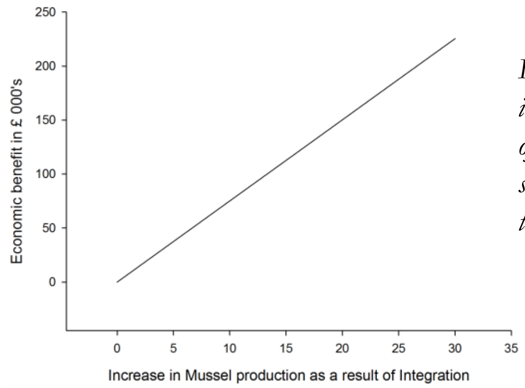

Figure 1. The relationship between economic benefit and the increased productivity of mussel production as a result of integration of mussel and salmon production. The figures are based on a simulation on a Scottish west coast salmon farm producing 600 tonnes pa of salmon and 16,000 m of mussel ropes [2].

Simulations of profitability of kelp/mussels/salmon production systems were compared to a monoculture of salmon in the Bay of Fundy [13]. From this simulation (run under a range of scenarios from optimistic to worst case) there is a 24% increase in profitability in co-culture systems compared to monoculture. It was also shown that the additional crops provided a buffer from financial loss when the primary crop ran into loss (worst case scenario). Co-culture of seaweeds has also been predicted to increase profitability of Chilean salmon production when external costs of nutrient emission are internalised [14].

A more preliminary analysis from the Scottish west coast of growing seaweed alongside salmon cages (*Palmaria palmata*) for human consumption showed that at a quoted market value of £0.5/kg fresh weight a one hectare plot would make a £15,000 loss [6].

In a public perceptions survey of integrated aquaculture [15], 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 sea food consumers would be prepared to pay 10% extra for IMTA produced mussels if they carried appropriate labelling [16].

Any such premium for integrated aquaculture products would need to be assessed and factored into economic models. This does however highlight the need for eco-labelling and certification for products of IMTA. When approached, Dr Smith, Chief executive of the Aquaculture Stewardship Council, stated that they had no plans to create any IMTA certification stating that their certification was for standards of production not methods of production.

Item	Quantity	Unit Cost	Lifespan	Annual cost
Longlines	*40*	*£95300*	*5*	*£19060*
Labour	*2 full time personnel*			*£35000*
Boat	*£20000*		*5*	*£4000*
Seed line	*100000 m @ 10 per km*			*£1000*
Shed, air, tanks, power drying facilities etc		*£20000*	*10*	*£2000*
Consumables				*£1000*
Admin incl insurance,licences, marketing etc				*£2000*
Maintenance costs				*£1000*
			TOTAL	*£65060*
Revenue	*100 tonne @ 50p kg*		*INCOME*	*£50000*

Table 1 Costs involved in managing a one hectare seaweed farm for culture of Palmaria palmata [6].

Additional economic impetus would come from the development of a nitrogen trading scheme within the aquaculture industry. Nutrient trading systems are becoming an important tool for improving coastal water quality in the US. Within Europe a possible existing mechanism to monetize the capacity of integrated aquaculture to reduce costal nutrients is through the extension of the EU agro-environmental aid program, whose framework could be extended to integrated aquaculture. Based on its ability to remove nitrogen through this scheme, 1 kg of live mussels could attract a subsidy of 0.11€ [17].

Attribute (Respondents)	Yes	No	Don't Know
Pay same price (649)	*61%*	*8%*	*31%*
Pay 10% premium (595)	*38%*	*21%*	*41%*
Pay 20% premium (471)	*18%*	*35%*	*47%*

Table 2 Pricing preferences of New York seafood consumers for IMTA-raised mussels sold with an eco-label [16]

Research and Innovation Recommendations
1) In products of co-culture with a proven market (i.e. blue mussels), determine the increase in production that can be expected through co-culture in a range of industry realistic scenarios.
2) Where products of co-culture have yet to develop a proven market such as seaweeds, undertake market research to determine possible markets and value chains for products.
3) Accurately determine costs to develop commercial scale production on new products such as macroalgae. Using data from 2 to determine if commercial scale co-culture for these species is currently economically viable.

Biosecurity

Questions have been raised concerning the biosecurity implications of culturing multiple species in a single location. These concerns can be split into 3 broad categories:

1) The co-culture species acting as a reservoir of infectious agents for the principle crop.

Infectious salmon anaemia virus (ISAV) [18]

- Blue mussels cohabiting with salmon (*Salmo salar*) infected with ISAV for 35 days tested negative for ISAV.
- Blue mussels were experimentally allowed to accumulate ISAV. Following exposure the number of ISAV positive mussels was recorded. Twenty-four hours post exposure ISAV was detectable only in 5% of the mussels tested, by 96 hours none of the mussels tested positive for ISAV.
- Blue mussels were allowed to accumulate ISAV and the hepatopancreas was injected into salmon 9, 24, and 96 hours post exposure to the virus. Those fish injected with the mussel 9 hours after exposure 76% tested positive for ISAV, after 24 hours it was 4%, after 96 hrs it was 0%.

These results suggest that mussels are not a reservoir host or vector of ISAV.

Vibrio anguillarum (vibriosis) [19]

Blue mussels were shown to accumulate *Vibrio anguillarum* in their digestive glands. Mussel pseudo faeces were shown to contain concentrated and infectious *V. anguillarum*. Juvenile Cod exposed to infected faecal material suffered 60-80% mortality. This indicated that in the co-culture of mussels and fin-fish, mussels may act as a reservoir of infections for *V. angillarium*.

Infectious Pancreatic Necrosis virus (IPNV) [20]

Mussels uptake viable virus slowly and shed viable virus through pseudo faeces. *Note: these results are from conference proceedings and as such the study has not been through a full peer review process.*

2) Accumulation of therapeutants, pollutants from principal species in the co-culture species. [21]

From a study in the Bay of Fundy, where mussels and kelp were co –cultured with salmon and tested for the accumulation of various pollutants and toxins:

Heavy metals **-** mussels from co-culture did not have significantly elevated levels of the 11 heavy metals tested for.
PCBs, DDTs and other organo-chlorine pesticide - concentrations in mussels and kelp from the co-culture site were below quantifiable levels

Therapeutants from principle species - Emamectin benzoate, oxytetracycline, cypermethrin, ivermectin, chlorotetracycline, tetracycline, sulphadimethoxine, and sulphadiazine were not detected in mussels or kelps grown in co-cultured species

3) Control of Parasites [22]

Laboratory experiments have shown that blue mussels are capable of ingesting the free swimming life stage (copepodids) of the sea lice *Lepeophtheirus salmonis*. In small scale experiments mussels ingested up to 62% of free swimming larvae.

Research and Innovation Recommendations
1) Comprehensive laboratory and field trials concerning the capacity of bivalves to act as disease reservoirs and vectors.
2) Test bivalves from Scottish fish farms for heavy metals, persistence pollutants and therapeutants.
3) Conduct laboratory and field experiments on the ability of bivalves to control sea lice by disrupting the sea lice life cycle.

Constraints and Opportunities of Integrated Aquaculture

Despite the wide academic acceptance of the concept of integrated aquaculture in academia and increasingly in industry, the lack of meaningful adoption by industry is indicative of a number of 'game stopping' constraints. In a stakeholder study (Table 3) the following constraints and opportunities were raised and ranked according to importance[23]. A number of these constraints are knowledge based, and where research has been conducted (see Issues of Special Interest section earlier) there is a lack of conclusive evidence to nullify the constraint. This analysis provides a useful framework for understanding the research requirement of aquaculture industry if integrated aquaculture is to be more widely adopted in a Scottish context. This study highlights an interesting disparity: the primary constraint is the financial cost associated with development while increased income generated from additional crops only ranks 7 in the opportunities. This may be indicative of an industry wide scepticism of the business case for integrated aquaculture. If this is the case, then perhaps the single most effective action to develop wide spread adoption would to be to prove the business case.

Rank	Constraints	Opportunities
1	*Financial costs associated with development*	*Reduced impact on the environment and downstream users, e.g. other farms*
2	*Availability of suitable land or water*	*Improved efficiency of resource use, e.g. nutrients and water*
3	*Decisions based on short-term financial appraisal*	*Reduced sediment and nutrient concentration in wastewater*
4	*Lack of funding, access to venture capital*	*Less energy consumed and waste generated in food production*
5	*Limited knowledge-base regarding design and management, e.g. optimal loading rates, harvesting strategies, disease management*	*Improved public perception; reconciling environmental and economic goals of different groups*
6	*Wastewater supply, e.g. nutrient flows not optimal or presence of chemicals, antibiotics or pathogens*	*Reduce the potential for farms to self-pollute*
7	*Discharge requirements; by-products from integrated systems may not comply with regulations*	*Increased income generated from additional crops based on same inputs*
8	*Market analysis and stimulation required*	*Meet expectations of managers regarding environmental protection and waste management*

Table 3: Stakeholder perceptions of the constraints and opportunities of Integrated Aquaculture. The table is adapted from Bunting 2007 [23]

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