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Editor's Note: I have recently taken over editorship of Aquaculture Update from Dr. Craig Clarke. I would like to thank Dr. Clarke for giving me this opportunity and for his many years of presiding over the production of this newsletter. I will be attempting to have three issues of Aquaculture Update per year (published in April, August, and December). If you have any ideas for an upcoming issue, I would be glad to entertain them. My contact information is at the bottom of this page.

Chris Pearce

Water Quality Interactions and the Implications for Integrated Finfish-Shellfish Aquaculture

Stephen F. Cross
Aquametrix Research Ltd., 2541 Conrad Road, Courtenay, British Columbia, Canada V9N 9N8
Tel: (250) 338-9255; E-mail: cross@aquametrix-research.com

The sensitivity of shellfish (bivalve molluscans) to a broad range of water-born materials (e.g. metals, complex organic compounds, suspended solids, bacteria) make them ideal candidates in the assessment of potential water quality impacts associated with salmon net-cage operations. The use of shellfish as biomonitors not only permits testing of the spatial influence of these substances in the marine environment, but also has important implications with respect to seafood safety, given their respective value in commercial (wild harvest, aquaculture) and recreational uses.

Shellfish aquaculture currently represents over 46% of the world mariculture production, and by all estimates is seen as having substantial potential for expansion through diversification, intensification, and technological innovation. While most bivalve mollusc farms currently comprise monoculture operations, there has been increasing interest in combining shellfish with other aquaculture species in an effort to develop, and balance, polyculture systems.

The primary objective of this study was to quantitatively document the culture performance and tissue quality of commercially important deep-water shellfish species (i.e. Pacific oyster, *Crassostrea gigas* and Japanese scallop, *Patinopecten yessoensis*) cultured adjacent to marine finfish aquaculture operations, and to determine (from a production viability and seafood safety perspective) whether integrated finfish-shellfish Multi-Trophic Aquaculture (MTA), or polyculture, is a viable option for the aquaculture industry of temperate regions. To explore the potential of this concept, this research comprised a number of components that addressed key issues that would require consideration for such commercial development. These included: (i) delimiting the oceanographic and physiographic characteristics of a culture site that might affect aquaculture performance and product safety; (ii) documenting shellfish aquaculture performance (growth, survival, taste, odor, texture) within the spatial influence of a finfish culture facility; (iii) quantifying the waste composition and loading from a finfish facility, including the spatial and temporal extent of these discharges; (iv) establishing the negative, bioaccumulation effects of waste discharge constituents on shellfish tissue quality; and (v) summarizing the environmental, social, and economic benefits of MTA systems given negligible and/or manageable interactive effects of these two species groups.

Oceanography and Physiography

Two study sites in coastal British Columbia were selected for the research program, one an Atlantic salmon farm site (located in an area anticipated to have strong tidal flows) and the other a Pacific salmon farm site (in an area of weaker tidal activity). To determine the potential pathways for waterborne contaminant transport at the two study sites, the physical oceanographic characteristics of the sites were documented at the onset of the study. Tidal circulation surveys of the entire study areas were conducted using a 300 kHz Acoustic Doppler Current Profiler (ADCP) in transect mode, with detailed lunar cycle exchange dynamics established using a bottom mounted, data-logging configuration of this instrument.

Tidal flow at one site was characterized as weak and bi-directional while data acquired at the other site revealed a strong and uni-directional tidal flow. A dramatic difference in tidal velocities, vertical flow components, and duration of tidal quiescence were described for the study sites, and subsequently used to explain differences in contaminant dispersion, dilution, persistence and hence bioavailabilty to the adjacent shellfish.

Oceanographic and physiographic site attributes were considered critical factors to the design of an effective Multi-Trophic Aquaculture (MTA) system. It is argued that the relationship between MTA system design and the environmental attributes of a site (tidal flow, bathymetry) could be used to maintain optimal conditions for aquaculture performance (health and productivity), taking advantage of sustained water quality, and optimal phytoplankton and/or seston flux (food resource for shellfish component) to the system. Such design considerations would also, presumably, minimize the potential negative effects of waste products (particulate and dissolved) that would be released to the water column from the finfish component of the system. Increasing flow velocity and vertical mixing would result in an increase in waste dispersion with a commensurate reduction in the localized persistence of such contaminant loads.

Organic Waste Composition and Flux

The sediment canister component of this research program provided a clear indication of the spatial extent of organic waste dispersion (solids fraction), and the influence of physical oceanographic characteristics on this process. A total of 15 canisters were placed at each study site, with stations including inside of the net cage, and along the shellfish longline from the cage perimeter to a distance of 225 m downstream. Paired canisters at each station included collection points at 15 m below the surface and one near the seafloor. Canisters were recovered at a 21-d interval, with residues measured (volume, weight) to provide an estimate of organic waste flux (settling solids component) from the finfish farm.

At the farm site affected by weak tidal flows, seafloor and mid-water fluxes were measurable to a downstream distance of 100 m and 60 m, respectively. The site with stronger flows revealed that dispersion occurred to a distance of 115 m at the seafloor and 20 m in the mid-water column region.

Analysis of the collected canister wastes indicated that phosphorus, calcium, carbon, zinc, cadmium, and strontium were constituents that were found at elevated levels at the farm sites with significant declines in concentrations with distance downstream. The dispersion pattern of these waste constituents was similar to that documented for the total waste fluxes, suggesting an association of these contaminant components and the pathway by which they enter and are dispersed within the receiving environment.

The total waste flux between the two study sites were not significantly different but did correspond, in magnitude, to the slight differences attributable to the species of fish grown, their specific feeding rates, and their feed conversion ratios. For the Pacific salmon farm, waste flux was estimated at 17.11 g m^{-2} d^{-1} while that for the Atlantic salmon site was 18.35 g m^{-2} d^{-1}.

An estimate of the organic waste fraction retained within the water column in either a fine particulate (suspended) or dissolved form, and hence that component which remained available to interact with adjacent (suspended) shellfish resources, was completed using detailed farm records and the canister data. This mass balance estimation suggested that 85.1% of the organic material (feed) entering the cage was used for fish growth/respiration, 6.8% was lost as settling solids to the seafloor, and the remaining 8.1% was retained in the water column and thus a fraction that could affect non-target species either directly or indirectly (e.g. via assimilative by-products; through trophic level transfers, etc.).

A similar mass balance evaluation of trace metal and chemotherapeutic compound pathways suggested that an estimated 12.9% of the zinc contained in feed, for example, would be released to the water column and hence potentially available for uptake. Furthermore, it was estimated that 98.6% of oxytetracycline is lost to the water column during and immediately post-treatment. However, the impact (and risk) of these periodic fluxes is dependent on initial concentrations (in feed), as well as the site-specific oceanographic influences that will determine *in situ* concentrations and hence the non-target species bioavailability.

Shellfish Performance

Shellfish test longlines were installed at both farm sites, each positioned downstream of the farm to allow the established shellfish to intercept any waterborne contaminants from the farm site. Scallops (*Patinopecten yessoensis*) and oysters (*Crassostrea gigas*) were placed at each of ten stations positioned along these longlines, which extended from the cage perimeter to 225 m downstream of each study site; an additional station was established within one of the system net cages to ensure signal detection of any waterborne contaminants. Seed and adults were deployed within Pearl nets and oyster trays to facilitate ongoing performance evaluation (growth/survival) and routine sacrificial sampling for contaminant accumulation estimates (45-d sampling interval).

Shellfish growth was neither impeded nor enhanced as a result of being cultured directly within the influences of the salmon aquaculture facilities. The lack of significant shellfish growth enhancement in this particular study, contrary to that documented by other similarly designed research initiatives, spawned a number of theories regarding the processes (and environmental conditions) under which organic waste material from a finfish operation might stimulate shellfish growth within the near-field region of such a facility. This avenue of speculation, which considered the selective feeding nature of non-siphonate bivalve species, included the effects of: (i) seston composition, concentration and the relative contribution/utilization of the farm-derived organic waste component; (ii) dissolved nutrient flux and possible indirect effects on localized phytoplankton composition and concentrations; and (iii) the hydrodynamic attributes of the site and the effects of system infrastructure on bioavailability of the seston fractions.

Members of a coastal aboriginal community were included in an organoleptic test of the shell stock grown at the salmon farm facilities over the 2-year production cycle. Taste, odour and texture were considered in a comparison with shellfish grown from a commercial shellfish farm far removed from any salmon aquaculture operation. Results of this study component demonstrated that shellfish palatability was not negatively impacted as a consequence of culture proximity to a finfish aquaculture facility.

Shellfish Tissue Monitoring

The shellfish monitoring component of this study revealed that trace metal constituents of the feed did become available to the shellfish, although the quantifiable accumulation of trace metals in these non-target species occurred only in close proximity to the cage system and only for the tested scallops (*Patinopectin yessoensis*). The levels found in the oyster (*Crassostrea gigas*) remained below, or equivalent to reference levels in all tissue samples analyzed.

Trace metal concentrations within scallops were significantly higher at the in-cage station (shellfish suspended among the fish), as compared with reference levels, suggesting that the *in situ* concentrations of these metals may have been sufficient to elicit a measurable accumulation response in close proximity to the discharge source (the fish). The trace metal constituents found in the suspended shellfish positioned downstream of cage system did not report any significant accumulations above that of background. These results were explained through a number of theoretical processes, that suggested that the: (i) dispersion of trace metals outside of the cage system occurs primarily within a settling waste fraction that is dissipated below the portion of the water column supporting the shellfish; (ii) trace metal loadings within the suspended field are of insufficient magnitude (concentration) to elicit a significant downstream accumulation response in the scallops, primarily due to the physical processes that dissipate these materials; and/or that the (iii) majority of the waterborne trace metals are bound within a fine particulate waste fraction that is selectively avoided by the shellfish in favour of a preferred seston diet.

In addition to the potential effects associated with the continuous contaminant flux to the water column (feed constituents such as micronutrients), this research also assessed the spatial effects of chemotherapeutic compound use and residue release to the receiving environment. Both shellfish species showed elevated tissue concentrations of oxytetracycline (OTC) at distances as far as 150 m downstream of the salmon net-cage system. This observable effect, well beyond the spatial zone affected by the settling organic waste component (and associated trace metals), further supports the mass balance estimation of this contaminant fraction being released primarily to the water column (either in a dissolved form or in association with fine, suspended particulates).

Uptake rates of OTC by shellfish ranged from 0.056 to 0.100 µg g^{-1} d^{-1} (winter – summer) with an associated clearance rate of 0.016 – 0.109 µg g^{-1} d^{-1} for the corresponding treatment periods. The comparison of uptake-clearance dynamics suggested a significant seasonal component to these processes. The summer uptake rate was approximately twice that of the winter rate, with an associated clearance rate of almost 10-fold faster. The significant seasonal differences were attributed to one or a combination of factors, including change in physiological activity between summer and winter months (e.g. shellfish filtration rates, lipid reserves), and/or to changes in water column properties such as temperature, salinity, and light intensity all of which could affect OTC degradation and hence the bioavailable levels maintained in the water column.

The physical and biological processes affecting contaminant uptake and clearance rates were identified as important considerations in the management of a proposed *integrated*-MTA system. A simple *Probable Effects Duration* (PED) model was developed on the basis of Uptake-Clearance-Persistence plots, illustrating the basis upon which temporal effects of water quality deterioration could be managed in such a system. The variables directly affecting PED include concentration (contaminant flux, bioavailability, and *in situ* levels), tissue uptake rate, tissue clearance rate, and time (contaminant persistence). Other factors that will affect the PED include parameters such as species under culture, physiological status, age, seasonality, a competing biotic component (e.g. plankton), and the oceanographic properties of the site (including water chemistry, light intensity, temperature, salinity).

Benefits of Multi-Trophic Aquaculture

Results of this research suggested that two options are available for developing MTA in coastal temperate waters; i.e. an *integrated* MTA system and/or an *adjacent* MTA system. The first approach (Fig. 1, upper portion) endorses true multi-trophic aquaculture, thereby enabling the integration of various trophic level species within a single culture system (i.e. *integrated*-MTA or *i*-MTA). This approach recognizes the potential for water quality interactions that may originate from the finfish component of the system, and as such could be designed to take full advantage of these interactions, so as to benefit through optimal individual component production while assimilating wastes of the finfish component and thereby reducing the environmental impacts of this culture activity. An *integrated*-MTA that incorporates a finfish component would also require recognition of the water quality interactions that could temporally (and differentially) affect food quality/safety in the other resident culture stock(s), whether shellfish, macrophytes, or another trophic level candidate for co-culture.

The second MTA option (Fig. 1, lower portion), in avoiding the potential for any waterborne contaminant interaction (albeit site-specific and temporal in nature), is to consider implementation of an appropriate, water quality exclusion zone (WQEZ) around the finfish component of the MTA system. In essence, the culture of shellfish and co-cultured species representative of other trophic levels, would not be permitted within the area considered at risk from waterborne contaminants originating from the finfish component of the MTA.

The development of a balanced MTA could add measurable environmental benefits to existing aquaculture systems, setting the stage for future production efficiencies and growth. Given a proper regulatory framework, including seafood (MTA products) and environmental quality surveillance, the potential water quality impacts on the shellfish component of a finfish-shellfish MTA (identified in this research initiative), and the associated risks over seafood safety, could be effectively managed to support this aquaculture evolution.

The results of this research initiative are currently being applied to the development of a small commercial-scale MTA site owned by an Aquametrix Research affiliated company in British Columbia. The proposed site is being designed as an R&D facility, allowing a long-term evaluation of MTA. Support for this ongoing "*sustainable aquaculture*" initiative has been provided from AquaNET, local First Nations, Provincial Ministries, DFO Science, and industry partners, with additional involvement from a number eNGO's in the USA under consideration.

Acknowledgements

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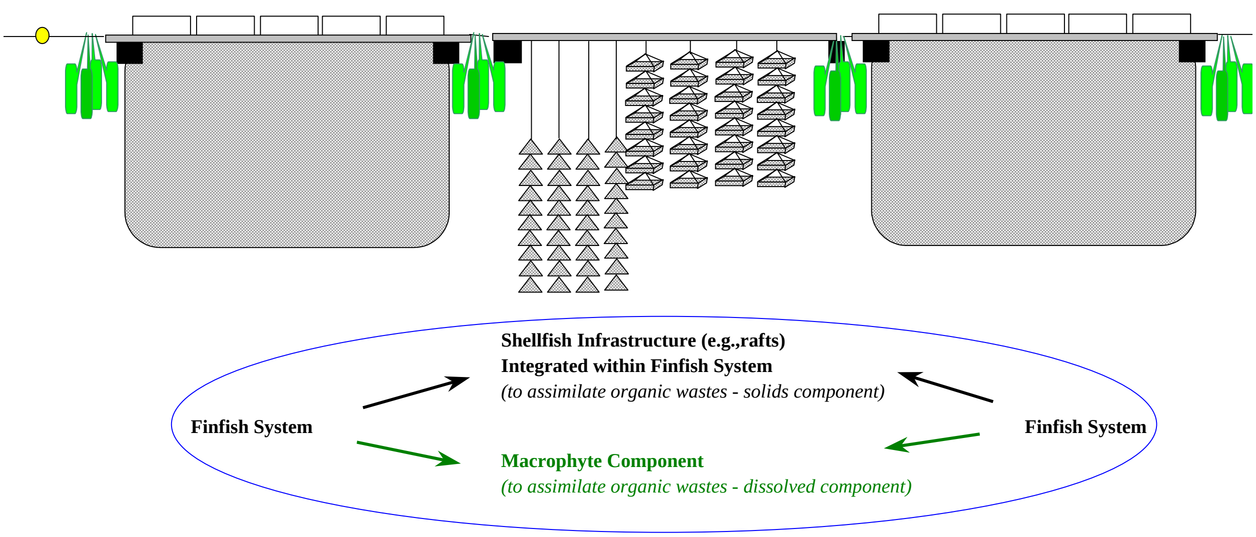
Fig. 1 Diagrammatic representation of the two proposed Multi-Trophic Aquaculture (MTA) approaches. **A**. An *integrated* system comprised of finfish, shellfish, and macrophyte culture components; **B**. An *adjacent* system portraying the same components given a Water Quality Exclusion Zone (WQEZ).

A. *integrated*- MultiTrophic Aquaculture (*i*- MTA) System; 3-level



B. *adjacent*- MultiTrophic Aquaculture (*a*- MTA) System; 3-level