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Weight ratios of the kelps, *Alaria esculenta* and *Saccharina latissima*, required to sequester dissolved inorganic nutrients and supply oxygen for Atlantic salmon, *Salmo salar*, in Integrated Multi-Trophic Aquaculture systems

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ABSTRACT

Estimates of seaweed nutrient sequestration ability in open-water, Integrated Multi-Trophic Aquaculture (IMTA) required to 'balance' nutrients from fish cages have typically assigned a specific nutrient load for a specific fish biomass. The resultant culture area and densities of seaweeds required for full equivalent nutrient sequestration may have meaning only to experienced aquaculturists. Consequently, a novel ratio model is proposed which determines the weight ratio of harvested seaweeds required to sequester an equivalent weight of soluble inorganic nutrients loaded per unit growth of fish. Soluble inorganic nutrient excretion from Atlantic salmon, *Salmo salar*, was estimated using a semi-stochastic nutritional mass balance approach. Oxygen demand was estimated using respiratory quotients. Nutrient contents of the IMTA kelps, *Alaria esculenta* and *Saccharina latissima*, were measured at harvest times, and net oxygen production was estimated using the photosynthetic equation. To quantify uncertainty, input parameters were assigned theoretical distributions (based on empirical or literature data) and the model was run using a stratified sampling approach (Latin Hypercube) over multiple iterations, to generate distributions of weight ratios for the various nutrients. A mathematical simulation of nutrient loading from a salmon farm over a full production cycle was estimated using mean loading values per unit growth, with monthly growth estimated by a thermal growth coefficient (TGC).
Results showed that one kilogramme of Atlantic salmon growth (large fish fed a typical commercial feed, ± standard deviation) resulted in the excretion of 29.49 ± 4.20 g nitrogen, 2.26 ± 2.25 g phosphorus and the respiration of 243.38 ± 48.28 g carbon. Dissolved oxygen requirements for 1 kg of growth were 455.29 ± 86.24 g. Salmon smolts placed in cages in spring and harvested 21 months later, load approximately 4 times more nutrients in the second grow-out season. The mean ratios of *A. esculenta* weight required to sequester nutrients excreted per unit weight of *S. salar* production were 6.7(±1.5):1 for nitrogen, 4.8(±3.0):1 for phosphorus, and 5.8(±1.4):1 for carbon. Oxygen could be supplied at a weight ratio of 4.1(±1.0):1. The mean ratios of *S. latissima* were 12.9(±2.7):1 for nitrogen, 10.5(±6.2):1 for phosphorus, and 10.2(±2.2):1 for carbon. Oxygen could be supplied at a weight ratio of 7.2(±1.5):1. *A. esculenta* appears to have almost twice the nutrient sequestration capacity per wet weight than *S. latissima*. However, culture densities of *S. latissima* are 1.5 times greater than those for *A. esculenta* and when spatially weighted this difference is reduced to 1–1.5 times.
Numbers of rafts for both kelp species required for full nutrient sequestration from a commercial scale salmon farm exceed the number of rafts which can be practically deployed within a typical site lease area. However, not all inorganic nutrients from cultured fish will be available to IMTA seaweeds, nor should 100% nutrient sequestration need be the only successful endpoint in such systems. These aspects should be considered when assessing the net value of kelps in open-water IMTA systems.

1. Introduction

Integrated Multi-Trophic Aquaculture (IMTA) is a form of food production, which connects cultures of different organisms, at different trophic levels (Chopin et al., 2001; Neori et al., 2007), by nutrient

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transfer through water (Neori et al., 2004). Nutrient waste from a fed component such as fish, supplies all or partial nutritional inputs for co-cultured species of commercial value. The aim of IMTA is to improve sustainability of fish culture, through nutrient sequestration (Reid et al., 2009), product diversification (Ridler et al., 2007), improved use of coastal 'real estate' (Barrington et al., 2009; Robinson et al., 2011) and there has also been some evidence of pathogen mitigation (Castro et al., 2004; Pang et al., 2006). The IMTA method and its associated variants — such as integrated agriculture–aquaculture (IAA), integrated peri-urban aquaculture (IPUA) and integrated sequential aquaculture (ISA) — and incidental IMTA (not purposely designed cultivation of species of different trophic levels situated in close geographical proximity), have been practised for centuries, mostly in Asia (Chopin, 2012). However, open-water IMTA has only been recently developed in the Western World as a commercial venture (Chopin, 2013).

The fed component of IMTA systems are often referred to as the Fed Trophic Level (FTL). Co-cultured species make up the extractive trophic levels. Nutrient waste from the FTL can be partitioned into three categories and consequently, at least three different extractive species groups or niches are required if all 'nutrient streams' are to be targeted. These nutrient categories and associated niches are as follows:

1) Dissolved inorganic nutrients from metabolic and respiration processes, or leached from solid organic waste, including forms such as ammonium (NH_4^+) and orthophosphates (PO_4^{3-}), can be absorbed by inorganic extractive species, such as seaweeds and aquatic plants.
2) Small suspended or slow sinking organic particulates generated from feed waste or faeces can be "captured" by organic extractive suspension-feeders, such as shellfish and some grazers.
3) Heavier settleable organic solids also generated from feed waste or faeces can be consumed by organic extractive deposit-feeders, such as sea urchins, sea cucumbers, sea worms and deposit-feeding fish (*e.g.* mullets).

The nutrient recovery efficiency of open-water IMTA will depend on temporal (*e.g.* deployment and grow-out times) and spatial (vertical and horizontal) scales of co-cultured species production, environmental conditions (*e.g.* current flow, temperatures and depth of euphotic zone), husbandry techniques, the number of niches filled, species selection, and the ratio of extractive species to FTL production, as described in this study. Consequently, reporting a single production level for an extractive species, required to sequester a given amount of FTL nutrients, is not possible for all operational scenarios. However, despite these complexities, measures of nutrient mitigation are essential for metrics of sustainability that can be used by environmental managers and these must be developed.

2. Weight ratio approach to quantify dissolved inorganic nutrient sequestration in open-water IMTA

There have been a few reports in the scientific literature on the relative nutrient sequestration potential of seaweeds grown beside fish cages (see Discussion). However, the measures in which this potential has been reported are typically based on site specific data such as production level, stocking densities, peak biomass and area. Arguably, such measures have little intuitive meaning for most stakeholders with the possible exception of highly experienced producers, "coastal managers" and researchers.

One method with the potential to avoid many site-specific operational complexities is to estimate nutrient sequestration values based on weight ratios. For example, given an amount of nutrient released per unit of FTL growth within a site lease area, what extractive species biomass would be required to sequester the equivalent load? This would then be reported as a ratio, such as x: 1 (Eq. (1)). Such a value is conceptually simple and arguably easier to apply for policy and farm management, and enable easier site specific calculations. There is, however, a significant assumption with inorganic extractive species and application of the ratio approach that should be noted. It assumes that we are not concerned with the removal of the actual soluble nutrient molecules excreted directly from the FTL, but only with net equivalents from the surrounding culture area. For example, while portions of excreted ammonium from fish will be directly sequestered by co-cultured seaweeds, it is difficult, in the absence of intensive data collection, to determine the amount sequestered directly from the fish versus that from ambient sources. It is unlikely that a molecule of ammonia from the FTL will be any different with respect to availability or function compared to one from the ambient environment. Determining such partitioning requires either the production of the co-cultured species at reference sites, of similar characteristics, for growth comparison with the IMTA site (to determine augmented growth), or the use of tracers such as stable isotopes. It is arguably impractical to collect such data for every site to accommodate the diversity of open-water IMTA production scenarios.

The ratio approach will not be applicable for all co-cultured species niches. In the case of heavier settleable organic solids, the use of nutrient equivalents cannot be used since we are concerned with the actual portions of the organic load settling in a discrete area in close proximity to fish cages. The potential for benthic hydrogen sulphide release is used as a regulatory indicator for impact potential in many jurisdictions (Chang et al., 2011). This is different from the nature of dissolved inorganic nutrients that will 'mix' to manifest a certain area-wide concentration, as the seaweeds will be involved in dissolved nutrient removal, regardless of the original nutrient source and this will be dealt with in the subsequent model.

3. Nutritional mass-balance nutrient loading for Atlantic salmon and sources of variation in estimates

The first step in modelling nutrient recovery in any IMTA system is determining the nutrient load of the FTL (*e.g.* salmon). A simple nutritional mass-balance approach is frequently used for fish to estimate nutrient loading (Papatryphon et al., 2005; Reid and Moccia, 2007) and the basic equations are detailed in the methods (Eq. (2)). This approach typically partitions mass-balance into nutritional categories of proximate composition, such as proteins, lipids, minerals and nitrogen-free extract (NFE). Often, NFE is a "catch-all" term used to describe the remaining category after the fractions of all other categories are subtracted from 1 (or 100, if percentages are used). It is mostly made of carbohydrates and may or may not include fibres depending on the breakdown. Proximate composition of the feed and whole body composition of the fish is required and the mass-balance calculations are done separately for each category.

Despite the relative simplicity of a mass-balance approach, there are many sources of variation in model inputs for nutrient loading estimates. Consequently, a semi-stochastic approach may be more suitable than a deterministic mathematical approach using static input values. We examine several potential sources of variation as a means to quantify uncertainty in model inputs and outputs.

3.1. Fish growth

Application of growth and waste production models for fish are reasonably well developed. The state of fish growth modelling has been recently reviewed by Dumas et al. (2010). For practical application in aquaculture, the amount of feed required to achieve a certain level of production is commonly used to predict growth. This is typically the Feed Conversion Ratio (FCR, feed/growth), although sometimes the reciprocal, Feed Efficiency (FE, growth/feed), is also used. If FCR and growth are known, the amount of feed used and waste estimates can be calculated. Feed wastage will need to be subtracted if it is an economic FCR (feed offered/growth). The FCR is useful for measuring an "end