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Environmental Impact of Aquaculture on Coastal Planktonic Ecosystems

Yngvar Olsen* and Lasse Mork Olsen

Trondhjem Biological Station
Department of Biology
Norwegian University of Science and Technology
Trondheim, Norway

*E-mail: yngvar.olsen@bio.ntnu.no

The main focus of this paper is the nutrient emission from cage aquaculture systems (CAS) in coastal waters and its potential environmental impact on pelagic ecosystems. The nutrient emission from CAS can be estimated based on mass balance using feed use, fish production, nutrients in feed and fish, and digestibility of nutrient components as input data. CAS release inorganic nutrients (NH_4 and PO_4), particulate organic nutrients, and dissolved organic nutrients. Pelagic ecosystems are primarily affected by the inorganic nutrients. A typical Norwegian salmon farm producing 1000 tonnes fish per year generated an amount of nutrient wastes comparable to a community of 7,500 to 10,000 people, with highest emission rates during summer. 3D hydrodynamic modelling is needed to estimate the dilution and transport of nutrients from CAS. Pelagic ecosystems have an inherent capacity of persistence, and smaller changes in nutrient input are mitigated through adaptive responses. There is an upper assimilation capacity above which pelagic ecosystems may loose integrity. The assimilation capacity of the pelagic ecosystem is mediated by two main mechanisms; the incorporation of nutrient in the organisms and a dilution process driven by hydrodynamics. There is a need for a systematic waste management from aquaculture in the future.

KEYWORDS cage aquaculture; nutrients; environmental impacts; eutrophication; pelagic ecosystem; hydrodynamics; nutrient assimilation; waste management

1. Introduction

There is now a growing attention and concern worldwide on societal aspects of the fast growing aquaculture industry. These concerns include for example animal welfare and particularly environmental impacts of marine aquaculture on coastal ecosystems (FAO 2006). Environmental concern and emerging new legislation, together with a growing competition for space in coastal waters, are becoming among the most important drivers for the development of marine aquaculture activities in western countries in the years to come. Two lines of development are apparent. Cage aquaculture systems (CAS) are gradually moved to more open sea locations, characterised by higher hydrodynamic energy, and land- and coastal based recycling aquaculture systems (RAS) are increasingly used for production of early stages and more local species. These trends of development are believed to continue (Olsen *et al*. 2008).

The social perception of the importance of an environmental problem is affected by the physical and biological characteristics of the coastal system as well as interactions with other important industries or human activities in the coastal zone. The major environmental concerns in Southern Europe are nutrient and organic waste emission from CAS in Mediterranean aquaculture producing mainly European sea bream and sea bass. Wastes from CAS are believed to cause ecosystem degradation and algal blooms. This is particularly regarded as a main threat for the blue water image of the stronger tourist industry, which is competing severely for space with aquaculture in coastal waters in Mediterranean countries (Katranidis *et al*. 2003). Escapes of fish from CAS and their interactions with fisheries are apparently not regarded as a major problem in Mediterranean countries, but these are the major environmental issues in many salmon producing countries (Muir 2005). Escaped salmon may contribute to the spreading of disease and parasites to wild stocks and interact negatively with these stocks during their spawning in rivers. Associations and industries involved in river fisheries of salmon are important stakeholders opposing for example the Norwegian salmon industry (Porter 2003; McGinnity *et al*. 2003).

It is important to realise that aquaculture is the first industry to suffer from an inadequate coastal water quality and environmental damage. The industry is thus very dependent on minimising its own potential pollution, but also the pollution originating from other human activities like other industry or urban runoff. The concept of an "Ecosystem-based Approach to Aquaculture" (EAA) has recently been introduced by FAO representatives in cooperation with the scientific community (D. Soto, pers. comm.). According to the principles of this concept, the fish farms should be managed as a part of the marine ecosystem as any other source or sink of organic matter and nutrients.

The scientific literature on impacts on sediments and benthic ecosystems is very comprehensive, and there is a general scientific understanding on which we may base assessments of state and dynamics, management, and monitoring measures. The potential impacts of wastes from aquaculture on water column ecosystems is far less studied, presumably because it has been difficult to identify and quantify such impacts (Merceron *et al*. 2002; Soto and Norambuena 2004; Maldonado *et al*. 2005; Dalsgaard and Krause-Jensen 2006). There is apparently no scientific concept established for assessments of state and dynamics, management, and monitoring measures for open coastal waters. There is thus not sufficient knowledge as to how specific measured environmental variables can reflect potential harmful impacts on open water ecosystems. Thus, this paper will focus on potential impacts in pelagic waters of nutrient emission from

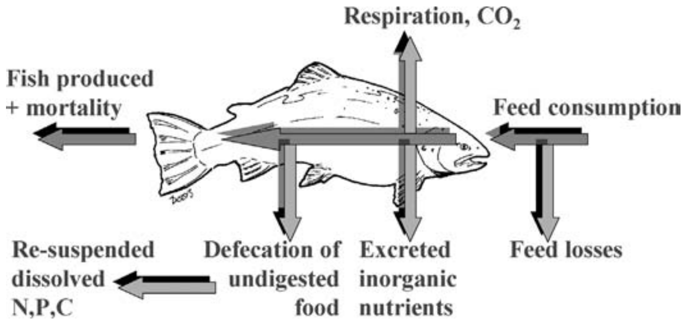

Fig. 1. Schematic allocation pathways of C, N, and P (energy and materials) in fish. Feed losses and mortality are relevant flows on the population level.

aquaculture and describe a preliminary general concept applicable for assessing such impacts.

2. Quantification of Nutrient Emission from CAS

The carbon (energy) mass balance for the flow of matter through a fish can be represented by the following simple mass balance equation:

$$I = A + F = G + R + F \quad (1)$$

where I is food consumed; A is assimilated food, or uptake in tissues; F is defecation; R is respiration, and G is growth and reproduction (all in terms of carbon or energy) (Fig. 1). The corresponding nutrient balance is expressed using the analogue equation:

$$I_{NP} = A_{NP} + F_{NP} = G_{NP} + E_{NP} + F_{NP} \quad (2)$$

where excretion of N and P (E_{NP}) replaces respiration. These general equations, together with knowledge on assimilation efficiencies of C, N, and P and the stoichiometric C:N:P composition of produced fish and feed are fundamental for estimating nutrient and carbon intake, metabolism, and losses from individuals of cultured fish.

The processes of respiration and excretion release inorganic carbon and excess inorganic nutrients, respectively, from fish tissues (assimilated matter) to the water. Respiration is a loss of carbon dioxide (CO_2) reflecting the metabolic costs of growth and maintenance of the organisms. The excreted N and P species are mainly inorganic nutrients wastes, i.e. urine (urea-N, PO_4) and ammonia (NH_4). These losses of assimilated N and P are instrumental to maintain elemental homeostasis in fish tissues.

The assimilated food is the portion of the food that is digested by the fish and taken up in tissues, and the assimilation efficiency (AE) is defined as (similar for N and P):

$$AE = A/I \quad (3)$$

The undigested food (faeces) passes through the fish gut undigested or partially digested. This fraction constitutes mainly particulate organic substances, including particulate forms of N and P, but some part is rapidly released in molecular dissolved forms in the water. The assimilated food supports growth and weight increment, and the growth efficiency (GE) is generally defined as (similar for N and P):

$$GE = G/I \quad (4)$$

This term expresses the efficiency by which the food ingested is converted to new biomass, similar, although inverse, to the food conversion ratio (FCR, feed consumed per fish produced) which is an operational term used in aquaculture.

The total wastes of carbon (TL_C) and nutrients (TL_{NP}) generated by cultured fish are expressed as:

$$TL_C = I - G = R + F \quad (5)$$

$$TL_{NP} = I_{NP} - G_{NP} = E_{NP} + F_{NP} \quad (6)$$

Respiration results in a release of inorganic CO_2, the emission of organic carbon (L_{OC}) wastes is most easily estimated as:

$$L_{OC} = I - A = I\,(1 - AE) \quad (7)$$

Values for AE of carbon or energy can be obtained from literature and in some cases from feed companies. For the formation of dissolved components from faeces, there is no formal way to distinguish these dissolved organic component (DOC) from the particulate organic (POC) waste components, but the particulate fraction is the most important (see below).

The corresponding estimate of organic nutrient wastes (L_{ONP}) from fish is:

$$L_{ONP} = I_{NP} - A_{NP} = I_{NP}\,(1 - AE_{NP}) \quad (8)$$

I_{NP} can be estimated based on total feed intake times feed NP contents. The assimilation efficiency of N can be assumed to be equal to that of protein, widely reported in literature and by feed companies (Anderson *et al.* 1995). The assimilation efficiency of P is widely reported as well, but more uncertain because of the addition of indigestible P compounds in the feed such as phytate P (Hua and Bureau 2006). As for carbon, there is no formal way to distinguish between dissolved organic nutrients (DON, DOP) and particulate organic nutrients (PON, POP) waste components originating from faeces, but the particulate nutrient fraction is the most important (see below).

The inorganic N and P release from the fish (L_{INP}) can be estimated as the difference between assimilation and production:

$$L_{INP} = A_{NP} - G_{NP} = (I_{NP} \times AE_{NP}) - G_{NP} \quad (9)$$

G_{NP} is N and P in produced fish, obtained as produced fish weight times N and P contents.

The waste production budget for an aquaculture facility differs from the fish budgets, as there is an additional waste component in the uneaten feed that may affect the environment. If mortality is significant, it should be included as well as a loss process of nutrients. Dead fish are usually collected for land deposition, and are as such not lost directly to the environment. To what extent a fish farm and the produced wastes affect the surrounding environment, depends on the size and type of the fish farm, the structure and functioning of the pelagic and benthic surrounding ecosystems, the overall management practice of the aquaculture facility, and perhaps most importantly on the hydrodynamics and physical conditions of the location.

The above method is most applicable for situations where the cultured organisms feed primarily on the added feed, and not on feed which are produced in the system (e.g., pond aquaculture systems). The method is robust and most accurate when there is adequate statistical input information on use of feed and fish production available.

If the statistical information on use of feed and fish production with time is more fragmented, the alternative to the mass balance model described above is a more general dynamic model describing fish metabolism, growth, and waste production (e.g., Fernandes *et al.* 2007). Such models are not that robust, but can be useful when input data are more fragmented.

Table 1. Characteristics and fate of nutrient components released from CAS.

Nutrient component	Acronym	Characteristics and fate
Particulate nutrients	PON and POP (particulate organic nitrogen and phosphorous)	• Whole feed pellets, small to very small particles originating from feed and fish faeces, other particles generated in fish farms (e.g., fouling). • Pellets and larger particles sink rapidly to the seafloor, are consumed by fish or other benthic organisms, or accumulate/decompose in sediments. • Small particles are suspended in the water column, consumed by filter feeders (mussels, zooplankton) and bacteria, within days. • Particles are not available for phytoplankton and macro algae.
Dissolved organic nutrients	DON and DOP (dissolved organic nitrogen and phosphorous)	Molecular nutrient components (organic), mostly complex chemical compounds, released from faeces particles and feed, and other biological activity. Stable components, available for phytoplankton on very long time scale. To some extent consumed by bacteria-microbial food web, can aggregate and sink (marine snow), relatively slow process.
Dissolved inorganic nutrients	DIN and DIP (dissolved inorganic nitrogen and phosphorous; NH_4 and PO_4)	Inorganic nutrients, i.e., ammonium and phosphate. Immediately taken up by phytoplankton, macro algae, and also by bacteria and used for growth, in the worst case they may cause algal blooms.

3. Characteristics and Fate of Nutrient Waste Components from CAS

Following the above considerations, CAS release nutrients as dissolved inorganic nutrients through excretion (NH_4 and PO_4), particulate organic nutrients (PON and POP) through defecation, and dissolved organic nutrients (DON and DOP) through resuspension from the particulate fractions (Table 1). There will also be a direct loss of uneaten feed (feed N and feed P). These different waste components will affect different parts of the marine ecosystem; feed losses and the larger faeces particles will sink and affect sediments and benthic communities whereas dissolved inorganic nutrients, dissolved organic nutrients, and small faeces particles affect the pelagic communities and the state and quality of euphotic waters.

Inorganic nutrients released can affect phytoplankton in euphotic waters quite

Table 2. Estimated loading rates of organic C and specified nutrient components from a hypothetical salmon CAS producing 1000 tonne fish per year. The farm area is 51 000 m^2 (160 × 320 m^2) the volume of the fish farm is 770 000 m^3, the overall FCR of the farm (feed used per fish produced) is 1.16 kg dry feed used per kg fish produced (Gillibrandt *et al.* 2002), feed input is 1160 mt $year^{-1}$, direct feed loss is 5% (Mente *et al.* 2006), feed P content is 1 % (Islam *et al.* 2005), feed N content is 6% (Islam *et al.* 2005), and feed organic C content is 50% (Elser *et al.* 2000). Input data for feed use and fish produced are obtained from the Norwegian Association of Fish Farmers and feed characteristics from the feed company Biomar.

Pelagic loading rates	Tonnes $farm^{-1}$ $year^{-1}$	g m^{-3} $year^{-1}$	mg m^{-3} day^{-1} (June–Sept)
OC-loading	20	26	100
NH_4-loading	28	36	140
PO_4-loading	2.1	2.7	11
Total N-loading	30	39	150
Total P-loading	3.0	3.9	15
DON + PON loading	17	22	86
DOP + POP loading	6.1	7.9	31

strongly in the upper mixed, illuminated layer of the water column where photosynthesis takes place. Organic dissolved nutrients are to a low extent available as nutrients for the phytoplankton. These nutrient components have long to very long residence times in marine waters (Bronk 2002; Karl and Björkman 2002). Particulate nutrients do not affect the phytoplankton in the mixed layer, but zooplankton is moderately affected all through the water column.

4. Nutrient Waste Emission from Typical Salmon Farm

The present section describes an annual mass balance for the main C, N, and P flows from a hypothetical salmon CAS producing 1000 metric tonnes wet weight of fish per year. Assumptions made in the calculations are shown in the legend of Table 2, which shows emission rates of the principal waste components from the fish farm. To put the numbers of Table 2 into a perspective, the total nutrient wastes generated of the fish farm corresponds to the emissions from a community of 7,500 to 10,000 people (2 g P per person per day, 13 g N per person per day, Norwegian standard). The N:P ratio of the total and inorganic nutrient wastes to open waters was found to be 10 and 13, respectively, which is above the Redfield ratio (7.2, by weight). Contrary to this, not shown in Table 2, the N:P ratio of the particulate wastes affecting sediments and benthic ecosystems was 2.7 and therefore far lower than the Redfield ratio. The majority of the N wastes is released to open waters (68% of total) whereas the majority of the P is accumulated in sediments (63%).

For the defined salmon farm, there was a pronounced annual variation in fish production and waste emission over the year (mean pattern for all Norwegian salmon farms), among others because of variable fish biomass and low temperatures in the winter period (Fig. 2). The annual variations of the N- and P-allocation into biomass (growth) and different waste components released from the salmon farm were at their maximum in August, with rates less than half of this maximum during the winter months. As a general trend, a lower proportion of the P of the feed (feed-P) than that of the N in the feed (feed-N) was excreted as phosphate and ammonia, respectively. Contrary, the fraction of particulate P, mainly released through defecation, was throughout higher than that of particulate N.

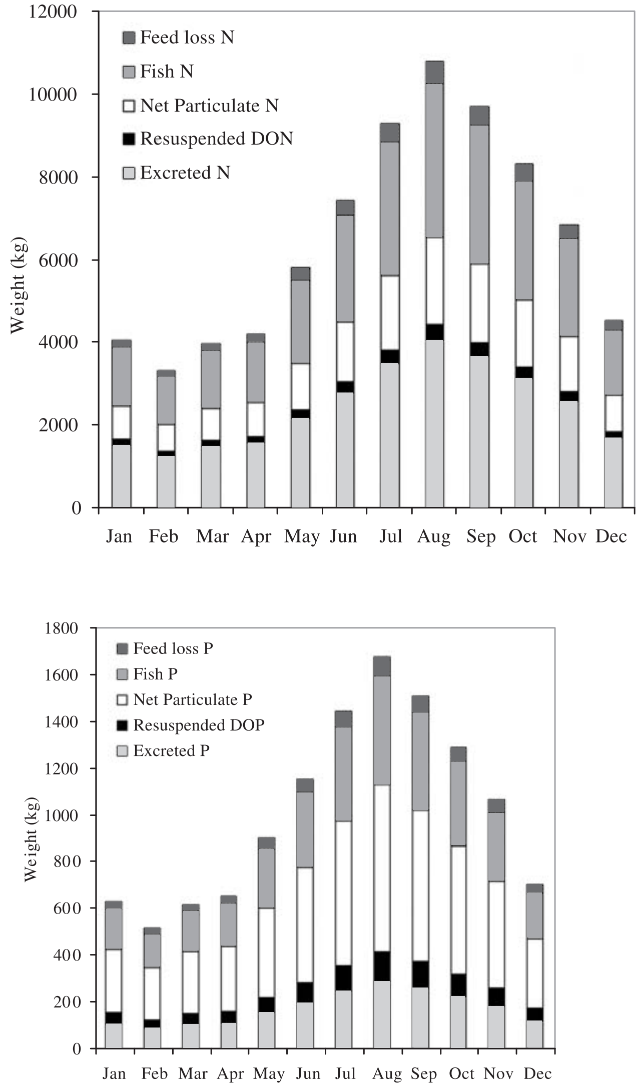

Fig. 2. Annual variation in nitrogen (upper panel) and phosphorus (lower panel) deposition in fish biomass and waste components for a hypothetical CAS producing 1000 tonnes salmon per year. The sum of the fractions equals the food nitrogen and phosphorous supplied.

The excretion of phosphate is highly dependent on the feed-P content, and the calculated P flows are relatively uncertain because of the problems in defining an accurate P content of the feed and its overall digestion efficiency (Sugiura *et al*. 2006). The values for N are probably more robust, because the protein content of the feed is less variable and its digestibility is higher and better known (Anderson *et al*. 1995). It is finally noteworthy that the rate of feed losses and the emission rate of dissolved organic nutrients (re-suspended DON and DOP), which has a low availability for phytoplankton (Table 1), are relatively low as compared to other waste emission flows.

5. Nutrient Assimilation Capacity of Pelagic Ecosystems

There is no general scientific understanding of how wastes from CAS distribute and affect water column ecosystems, and there is a poor quantitative understanding of how these nutrients affect the structure and function of the pelagic ecosystem (Cloern 2001; Olsen *et al*. 2006). This lack of quantitative knowledge means that there is no scientific base for monitoring and managing environmental effects of CAS on open waters, meaning that management must comply with the principle of precautionary approach.

It can be hypothesised that the assimilation capacity of the water column ecosystem is mediated by two main mechanisms:

- Food web response: Nutrient uptake and assimilation by phytoplankton, with successive trophic transfers of energy and materials (e.g., nutrients) in the planktonic food web to the higher trophic levels.
- Hydrodynamics: Transport and dilution of nutrients and plankton organisms mediated by hydrodynamics at production sites and their surrounding, downstream water masses.

The dilution mechanism is independent on the organisms of the water column ecosystem; major physical forcing processes drive hydrodynamics. The assimilation capacity of the planktonic community is, on the other hand, strongly dependent on hydrodynamics, because dilution leads to a continuous reduction of nutrient concentrations and biomass, and therefore also to an increase in capacity of nutrient assimilation in the pelagic community. Both mechanisms are accordingly working in concert. Nutrient uptake and allocation in planktonic food webs and hydrodynamics are the fundamental processes determining the assimilation capacity of the water column of coastal and open waters.

5.1. Food web response

All ecosystems have an inherent capacity of persistence, and smaller environmental changes are mitigated through adaptive responses of the organisms. Major changes in ecosystem structure and function, whether it is reversible of irreversible, will only take place if the environmental signal, or the environmental interaction, is strong and sustained. For the planktonic ecosystem of the water column, we may deduce that nutrients are efficiently assimilated without any harm as long as the input rate remains below a critical upper level.

Enhanced inorganic nutrient supply to pelagic ecosystems results in a stepwise process where the first step is an increased nutrient uptake in phytoplankton (and bacteria) followed by an increased growth rate (i.e., primary production). If the zooplankton grazing rate of phytoplankton is not too high, the phytoplankton biomass may accumulate and increase, leading to higher food concentration for all groups of heterotrophs, and in turn to successive responses in their feeding activities and growth. It will most commonly take some 3–7 days before an increased nutrient supply rate results in an increased biomass, which is the last step of the chain reaction. This means that the effects normally are becoming realised far downstream of the nutrient source.

The typical responses in primary production and accumulated phytoplankton biomass in stagnant NE Atlantic coastal waters are illustrated in Fig. 3. There is a close to linear response below N loading rates of 11–18 mg N m^{-3} day^{-1}. Open dynamic systems will respond differently, advection and vertical mixing will reduce the response quite pronouncedly for biomass, dependent on the mixing rates. The response in primary production is less sensitive than biomass for physical mixing processes and grazing (Olsen *et al*. 2006).

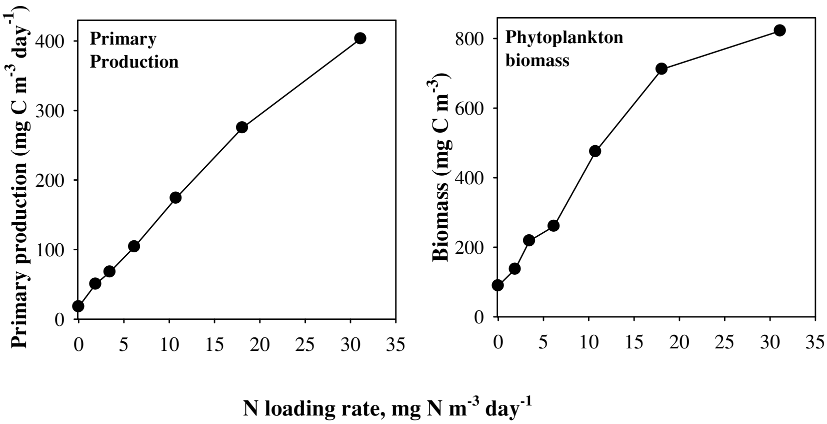

Fig. 3. Primary production (left) and phytoplankton biomass (right) as functions of N loading rate in stagnant NE Atlantic plankton ecosystems. (Norwegian data taken from Olsen *et al.* 2006).

The responses and trophic interactions of the heterotrophic planktonic food web following enhanced nutrient input are complex, but the bottom line is that the food web acts like a buffer which, within certain limits, may mitigate negative ecological effects of enhanced nutrient input, for example any extensive blooms of phytoplankton. The main functional components of the planktonic food web will respond in a predictable way to increased nutrient supply, although not on species level (Fig. 4). The increased primary production represents increased food availability for the heterotrophic plankton groups (i.e., zooplankton and bacteria). The upper panel of Fig. 4 illustrates a representative flow network (structure and function) for the normal, undisturbed situation in the planktonic food web of NE Atlantic coastal water. The lower panel illustrates a situation with a nutrient supply 4–5 times above the natural level. The main take-home message of Fig. 4 is that enhanced nutrient supply affects carbon flows between the heterotrophic functional components more strongly than biomass of these functional groups. The phytoplankton biomass (not shown) is responding more strongly than the heterotrophic biomass (Olsen *et al.* 2006), as indirectly indicated by the increased availability as food for zooplankton in the figure (input arrows). An apparent pattern of Fig. 4 is that structure and function of the microbial food web (bacteria, picocyanobacteria, small protozoans) is responding very little to nutrient addition. It is the larger groups of phytoplankton, metazoan, and protozoan (ciliates) grazers that primarily respond.

The most important message of Fig. 4 is the very pronounced increase in sedimentation rate that follows enhanced nutrient input. This flow of dead organic matter to deepwater and sediments represent an organic loading that becomes important for the oxygen requirements and concentration in aphotic waters and the sea floor communities. A non-linear, accelerating increase in sedimentation per primary production reflects the fact that the zooplankton grazers, at some point of nutrient input, are not any more able to consume, and efficiently remove, the enhanced primary production. A high sedimentation fraction of primary production is an indication that the planktonic ecosystem is no longer able to assimilate the enhanced nutrient input very efficiently.

Somewhere in between the loading rates of 3 and 20 mg N m^{-3} day^{-1}, we hypothesise

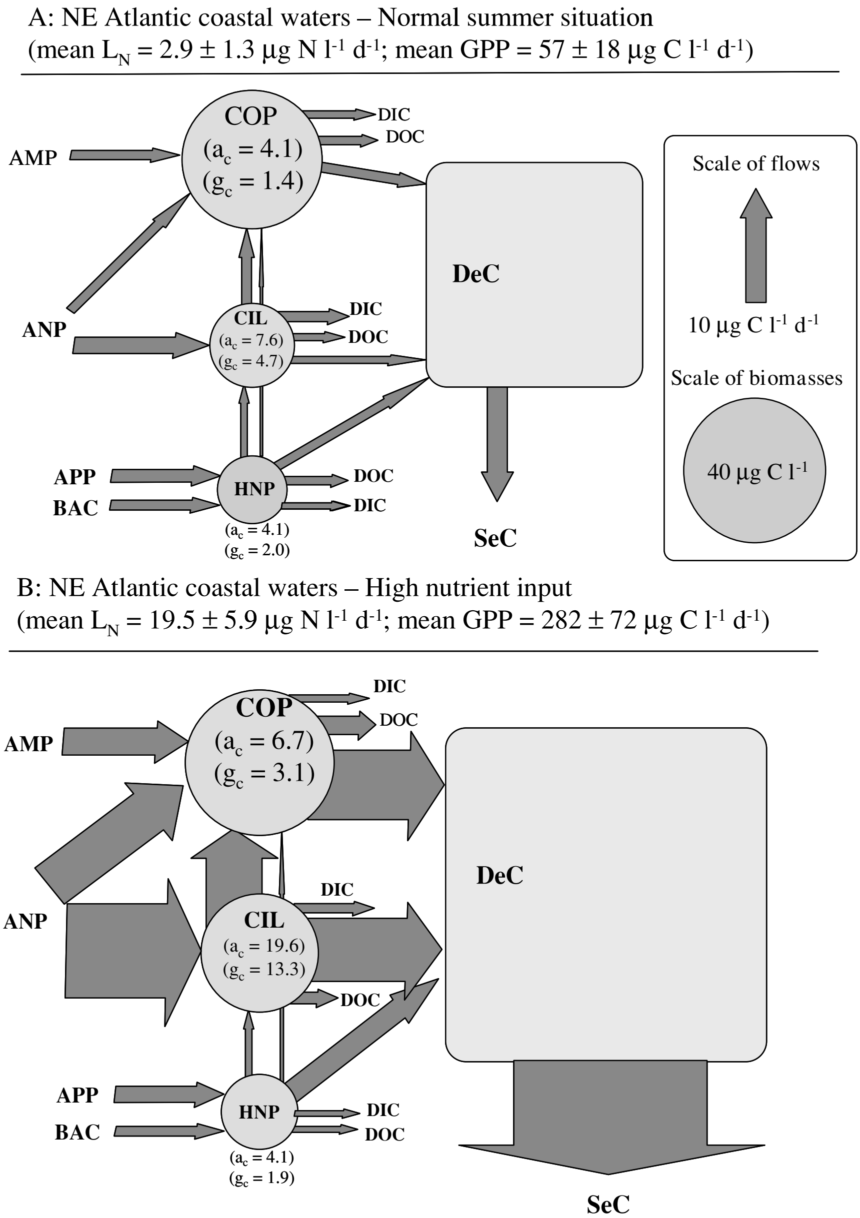

Fig. 4. Schematic view of carbon flow networks during (A) a normal summer situation in NE Atlantic coastal waters and (B) conditions of high nutrient input. Arrows show flows, boxes show biomasses (and their allocation of energy). AMP: feeding of large sized phytoplankton (20–200 µm), ANP: feeding of medium sized phytoplankton (2–20 µm), APP: feeding of small sized phytoplankton (<2 µm); HNP: heterotrophic nanoplankton (<20 µm); CIL: ciliates, main constituent of microplankton; COP: copepods, main constituent of meso-zooplankton; DIC: CO_2 release (respiration); DOC: released of dissolved organic components; DeC: release of particulate organic components; SeC: sedimented carbon; ac: assimilation rate; gc: growth and reproduction rate. All concentrations are expressed in terms of mg C l^{-1} and rates as mg C l^{-1} d^{-1} (taken from Olsen *et al.* 2007).

a critical nutrient loading rate (CNLR) which cannot be exceeded without loss of ecosystem integrity. The food web organisms are capable to assimilate efficiently the nutrients input without major exports to sediments below this critical rate, but not above. There is so far no generally accepted method to determine a CNLR for open coastal waters experimentally or empirically, and there is no published value, as far as we understand. There is, however, evidence showing that the primary production and the zooplankton feeding rates in stagnant systems both level off for volumetric loading rates around 1 mmol N m^{-3} day^{-1} (14 mg N m^{-3} day^{-1}) in NE Atlantic coastal waters (see Fig. 3 and Olsen *et al*. 2006).

5.2. Hydrodynamics

A cage fish farm represents a point source of nutrients to the surrounding water. The hydrodynamic energy and the depth of the site will, to a great extent, determine the water volume that receives the daily nutrient emission of wastes. Due to coastal and tidal currents, coastal seawater is rarely or never stagnant. Usually the current velocity varies below 25 cm s^{-1} (Carroll *et al*. 2003). The currents will dilute the water in the cages and the nutrient waste flows and broaden the deposition area considerably.

The pattern of water currents in coastal waters is complex, and cannot easily be deduced, even after extensive field surveys. As a first approximation for estimating the receiving water volume of our defined salmon farm, we may assume that water are drained through the cage farm in a plug flow pattern with no further mixing downstream of the farm site (see legend of Table 2). If water enters the cage area directly from the length side, and there is no major resistance in the cages, Fig. 5A shows the number of water exchanges and the resulting total volume passing the cage farm as a function of the water current velocity. Already water currents of 10 cm sec^{-1}, which are relatively slow, result in a high frequency of water renewal and a total exchanged volume of more than 50 million m^3 per day. This is for sure an underestimate of the real receiving volume, because the nutrients will become continuously exchanged with and diluted in neighbouring water masses downstream of the fish farm.

The volumetric loading rate (L_{VOL}) of inorganic nutrients is defined as the mass of nutrients released per volume of water per day. Quantification of the loading rate (mass of nutrients released per farm per unit of time, L_{Time}) and the receiving water volume (V, m^3) allow estimation of L_{VOL} for inorganic N and P (Fig. 5B), which decreases rapidly as the water current velocity increases. The hypothesised critical loading rate (see above) to coastal waters is 14 mg N m^{-3} day^{-1} (10–20 mg N m^{-3} day^{-1}, P in Redfield proportion). Another important reference is the natural supply rates of nitrogen to euphotic coastal waters. This value has been estimated to 4 mg N m^{-3} day^{-1} in a 5-year fertilisation experiment in a coastal lagoon off Central Norway (sedimentation measurements, seasonal mass balance).

With the critical and the natural loading rates in mind, Fig. 5B reveals that the volumetric nutrient loading rate of water passing through the fish farm will remain below the critical value as long as the water current velocity is >2 cm sec^{-1}, which is indeed a very low velocity. The fish farm will contribute to a loading rate comparable to the nature when the water current velocity is around 5–6 cm sec^{-1}. These calculations assume that there is no further mixing of water downstream of the fish farm; they therefore represent worst-case situations.

The exercise illustrates how important hydrodynamics are to mitigate negative environmental effects of nutrients released from salmon fish farms and other point sources of nutrients. If the production conditions were stagnant, the nutrient concentration following one day of emission would correspond

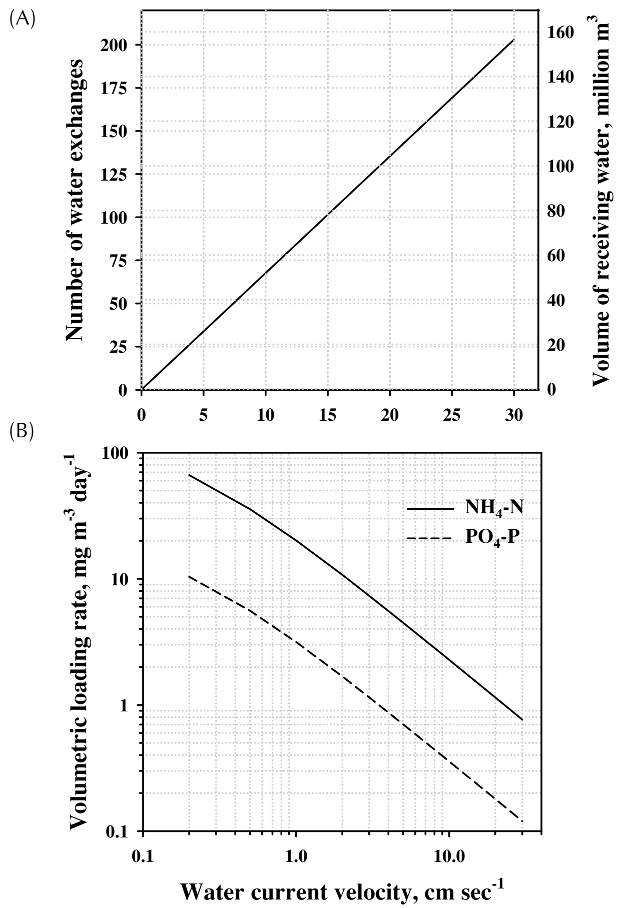

Fig. 5. Water exchange (A) and volumetric loading rates of N and P (B) as functions of the water current velocity (revised from Olsen *et al.* 2005).

approximately to a spring bloom event in Atlantic waters (typical DIN concentration of 140 mg N m^{-3}). It is easy to understand that this situation would have become an immediate disaster for both the salmon and the producer.

This type of exercise clearly concludes that advanced 3D hydrodynamic modelling is needed to estimate the mean volumetric loading rates and to demonstrate the spreading pattern of the excess nutrients from the fish farm to the surrounding waters more consistently. This is particularly important for nutrient assessments undertaken on a regional scale, with more than one fish farm draining to the same body of water.

5.3. Integrated scheme for food web and hydrodynamics

Food web and hydrodynamic contributions to the assimilation capacity of the water column ecosystem are schematically integrated in Fig. 6, forming a conceptual operational graphical tool for risk management of the water column ecosystem. In the "water current velocity–nitrogen loading rate"-space described as Area I, water dynamics are strong enough to maintain nutrient loading

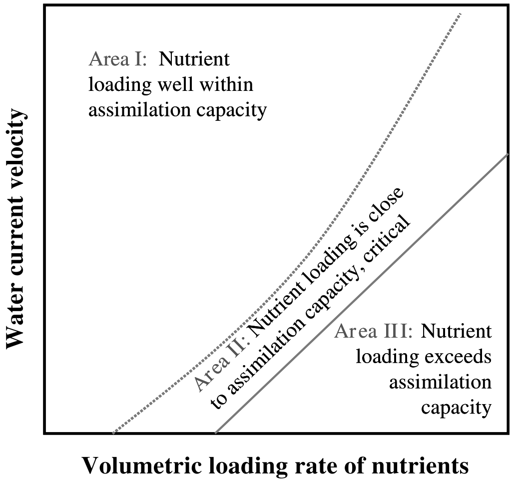

Fig. 6. Conceptual relationship describing the ability of the water column ecosystem to assimilate nutrient input as a function of the volumetric loading rate of inorganic nutrients and the water current velocity. Area I: Water dynamics are strong enough to maintain nutrient loading within the limits of the assimilation capacity of the water column ecosystems; Area II: The critical zone where loading rate is coming close to the critical nutrient loading that exceeds assimilation capacity. Situations represent increased risks and calls for special attention and a precautionary approach; Area III: Nutrient loading rate exceeds the limits of the assimilation capacity; the water column ecosystem can loose its integrity, which may cause harmful coastal eutrophication. The figure is preliminary, slopes and exact *x*-axis intersections of the indicated lines are unknown.

below the limits of the assimilation capacity of the water column ecosystems. In Area III, the nutrient loading rate exceeds the limits of the assimilation capacity of the pelagic ecosystem, the loading rate is then above the critical level (CNLR), and the water column ecosystem can loose its integrity, sedimentation rates are strongly enhanced, and harmful coastal eutrophication may occur. In the space described as Area II, the loading rate is coming close to the CNLR where nutrient loading exceeds the assimilation capacity. This situation represents increased risks and call for a precautionary approach. The solid curve expresses that the CNLR will increase with strong hydrodynamics.

The concept illustrated in Fig. 6 is preliminary. It will most likely intercept the L_{VOL} axis in 10–20 mg N m^{-3} day^{-1}, but the slope of the indicated line is not known. Moreover, the axis legends are so far accidentally chosen. Another proxy for hydrodynamic energy may be more suitable than the water current velocity. The volumetric loading rate can be translated into a standing stock of fish in fish farm. An ultimate R&D challenge is to examine different response variables for hydrodynamic energy and to quantify the boarders of the areas in Fig. 6.

6. Monitoring and 3D Modelling of Nutrient Mixing

Monitoring techniques, which allow assessment of pelagic waters over a wider geographic scale, are paramount for detecting potential impacts from nutrient sources like CAS downstream of the farm. The most apparent options are regional scale satellite imaging and 3D hydrodynamic modelling. Satellite images can provide real situations for phytoplankton blooms in surface waters

Table 3. Hydrodynamic characteristics and mean excess nitrogen concentrations of the 3 virtual salmon farms studied. Values express the concentration of excess N in the water occupied by the fish cages (hot-spot, one model grid of 160 × 320 m^2). The situations are representative for farms producing 1000 tonnes per year, which is well below today's production (up to 9,000 tonnes per year), but the results nevertheless demonstrates the options of the method. PON concentration in undisturbed coastal waters is set to 60 mg N m^{-3}, which is representative for the region. From Olsen *et al.* (2005), model data provided by D. Slagstad, SINTEF.

Fish farm number and location		Location conditions	Excess N in farm hotspot, mg N m^{-3} (mmol N m^{-3})	% Excess N of natural PON in farm hotspot (%)
1.	Langøya, outer exposed area	Strongly exposed, water is efficiently mixed with open the ocean	0.6 (0.04)	<1
2.	Langøysundet, a straight between islands	Tidal driven water exchange, efficiently mixed	6.4 (0.46)	11
3.	Eidsfjorden, a relatively stagnant fjord bottom	Unidirectional, steady water currents	17.9 (1.3)	30

at any given time, but it cannot easily distinguish between the highly variable natural nutrient supply and the optional anthropogenic signal. 3D hydrodynamic models produce a virtual world, not a real one, but such models can cover the entire water column continuously with time over any geographic region. Moreover, modelling allows us to distinguish between natural and anthropogenic signals, and it can potentially predict phytoplankton production and effects on higher trophic levels. Models can accordingly be run with and without nutrient emission from fish farms included, and the difference, termed the "excess" nutrient concentration, can be estimated right away. Modelling are also well suited to assess the integrated effects of all CAS and other nutrient sources located in a region, and accordingly instrumental tools for ecosystem-based management of aquaculture. Classical measurements must be used to validate the major trends found by satellite images and modelling at specific locations.

A modelling study examining loading and spreading of inorganic N from three hypothetical fish farms in Norway can serve to illustrate how a 3D simulation hydrodynamic modelling can be used to assess concentrations and distribution of released inorganic N and P from CAS (Olsen *et al.* 2005) (Table 3). The model predicts the concentration of excess N, i.e., the inorganic N released from the fish farm, whether it is dissolved or taken up by organisms after being released.

The mean excess N concentration at the farm hot-spot (see the legend of Table 3) in the outer exposed site at Langøya showed very low N concentrations, values that would not be measurable using analytical techniques (compare with the plug flow system, Fig. 5). Nitrogen was immediately dispersed, and neither enhanced primary production nor enhanced phyto-plankton biomass could be traced downstream of the farm in detectable amounts (not shown). Phosphorous will show an identical pattern of variation.

The excess N concentration inside the farm situated in Langøysundet, a strait between islands, was higher, corresponding to 11% of the natural PON concentration at the site (see legend of Table 3). Tides moved the water back and forth in the strait, and the surrounding water masses on both sides were to some extent affected locally (<1 km). The hydrodynamic forces were still strong, and the nutrients were widely spread. The residence time of the water was too short to allow a significant enhanced primary production and phytoplankton biomass around the fish farm (data are not shown).

The third site Eidsfjorden, which is a relatively stagnant fjord bottom, was characterised by regular anti-clockwise water currents with a main pattern not much affected by the tidal cycle. The concentration in the farm oscillated, however, quite pronouncedly, meaning that water current velocity varied with tides. The fish farm affected the water masses downstream of the site, and the mean hot-spot concentration of excess N was around 30% of the natural PON concentration. Excess N, primary production, or biomass did not significantly affect the outer water masses of the fjord. Hydrodynamics were surprisingly strong downstream of the farm along the north coast of the fjord, and the resources were rapidly spread to large water masses. There is not much space for a bigger salmon farm on this site, which might be suitable for integrated aquaculture of mussels (Whitmarsh *et al*. 2006).

7. Concluding Remarks

As aquaculture continues to grow, there will be a need for a more comprehensive waste management, not only for CAS, but for other systems as well. The means available for reducing the potential environmental impact is highly diverse and include feeding management, site selection, alteration of site, and an active use of wastes from feeding aquaculture to produce organisms on other trophic levels, organisms that can take advantage of the wastes from CAS (Integrated multitrophic aquaculture). The environmental impacts of sediments and benthic ecosystems are relatively well understood and managed, but there is a need to improve the general understanding of how pelagic ecosystems are impacted in order to establish a science-based management and monitoring practices for open waters. This is important for the societal perception of aquaculture, but also for the industry itself which require pure water for its activity.

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