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Balancing marine aquaculture inputs and extraction: Combined culture of finfish and bivalve molluscs in the open ocean

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Abstract Enrichment of the water column with dissolved nutrients and of bottom sediments with organic matter as a result of culturing finfish in sea cages have been identified as real and potential environmental impacts of fish culture. While severe impacts have been documented in shallow, poorly flushed waters, proper siting of sea cage operations generally results in only minor localized impacts to the benthic community on the sea floor directly beneath the cages. None the less, the perception of environmental groups and regulatory agencies in the U.S.A. that fish waste and uneaten feed will impact the marine environment regardless of siting has affected the expansion of existing sites and the establishment of new sites. In order for the industry to expand to meet the growing demand for seafood, measures to mitigate these impacts must be taken. One possible solution is to balance inputs of feed with extraction of biomass of organisms such as marine plants and bivalve molluscs that do not require external feed application.

In 1999, the University of New Hampshire established the Open Ocean Aquaculture Demonstration Project. Funded by the National Oceanic and Atmospheric Administration, the project was designed to provide a commercial scale demonstration and research site for open ocean aquaculture in the northeast U.S.A. The project is an integrated, multi-disciplinary, regional effort that includes biology, oceanography, engineering, sociology, economics, technology transfer, and education. While the development of technologies for finfish and shellfish production in offshore environments is central to the mission of the project, demonstration of the environmental sustainability of open sea culture is critical to the social acceptance of industry development.

Since 1999, the project has produced harvests of several species of finfish using submersible sea cages and six crops of molluscan shellfish (primarily blue mussels) using submerged longlines in close proximity to the sea cages. While not considered true polyculture, the harvest of the filter feeding bivalve molluscs represents a net removal of nitrogen, carbon and phosphorus that can be used in mass balance to offset the addition of these nutrients from finfish feeding. In this paper, data the potential for balancing inputs associated with feed application and fish wastes with extraction of fish and bivalve biomass will be examined.

Key words: bivalve mollusc culture, finfish culture, sea cages, waste feed, nitrogen

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As the world's human population continues to grow, the demand for food, and especially protein, increases correspondingly. The protein derived from seafood accounts for 13 % to 16 % of the human diet worldwide. In other words, in order for high quality protein production to keep pace with population growth, seafood production must increase. Addressing this shortage of seafood requires more production from either capture fisheries or aquaculture. By most accounts production from capture fisheries is unlikely to increase from the current levels (FAO, 1998), therefore aquaculture will become an increasingly important source of seafood production.

Marine aquaculture systems are quite diverse, ranging from highly controlled land-based systems that recycle water and remove and treat wastes to open water cages that release wastes directly to the environment. Species produced in the marine environment are also very diverse, and include seaweeds, bivalve molluscs, echinoderms, crustaceans, and finfish. As with all concentrated food production systems, aquaculture can potentially have negative impacts on the environment, however, the severity of impacts depends on the culture system employed, the location, the species under cultivation, and husbandry practices. In the marine environment, negative impacts have been attributed to all forms of aquaculture, though finfish aquaculture has been the primary target of most of the critics of the aquaculture industry (Goldberg and Tripplett, 1997). One of the negative effects attributed to finfish culture is enrichment of the water column with dissolved nutrients, resulting from the decomposition of uneaten feed, and from metabolic wastes produced by the fish (Fig. 1).

While the amount of dissolved nitrogen discharged from fish farms may be locally significant and could potentially impact poorly flushed shallow embayments by increasing phytoplankton production, the volume of the discharge relative to other human sources of nitrogen to coastal waters is negligible (McVey *et al.*, 2002). In well flushed areas, it is unlikely that nitrogen addition from finfish aquaculture would have any impact on trophic conditions of the receiving waters (Sowles and Churchill, 2002). None the less, the perception of environmental groups and regulatory agencies in the U.S.A. that fish waste and uneaten feed will impact the marine environment regardless of siting has affected the expansion of existing sites and the establishment of new sites. In order for the industry to expand to meet the growing demand for seafood, measures must be taken to address these environmental concerns.

The salmon industry worldwide has greatly reduced nitrogen discharge by developing better feed formulations, reducing the amount "fines" or small feed particles by improved feed handling and delivery methods, and by monitoring the feeding behavior of the fish with video systems and ceasing feed delivery when the fish stop feeding (Sowles and Churchill, 2002). Another possible solution is to balance inputs associated with fish feeding with extraction of biomass of organisms such as marine plants and bivalve molluscs that do not require external feed application. This approach has been referred to as integrated aquaculture and is attracting increasing attention as a way to mitigate the real and perceived impact of finfish culture (McVey *et al.*, 2002；Chopin *et al.*, 2002).

The concept and conduct of polyculture or integrated aquaculture is not new, and has been

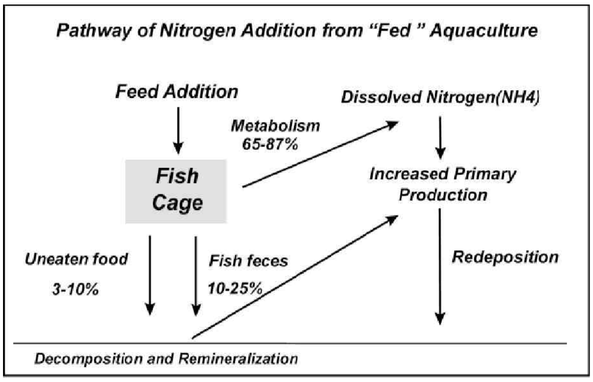

Fig. 1. Pathway of nitrogen wastes generated by the addition of fish feed in open water systems

practiced for centuries in Asian countries (Chopin *et. al.* 2002). While the rationale for considering integrated aquaculture today concerns mitigation of nitrogen additions from fed aquaculture, the result is similar, in that one species benefits from the waste products of another. With dissolved nitrogenous wastes, plants such as seaweeds benefit with enhanced growth from the increase in essential nutrients. Harvesting plant biomass for food or for pharmaceutical or industrial extracts constitutes mitigation of the nitrogen added through feed addition. Bivalve molluscs can also incorporate the waste nitrogen, however the pathway is indirect, relying on an increase in phytoplankton production resulting from the nitrogen additions (Yarish *et al.*, 2002).

Integrating seaweed or bivalve culture with finfish culture provides a mechanism for removing some of the added nitrogen resulting from feed introduction through harvest. The pathway of waste nitrogen in integrated systems is illustrated in Fig. 2.

The effectiveness of extractive aquaculture species in mitigating nitrogenous wastes produced by finfish culture has been demonstrated for closed-system, intensive land based culture (Shpigel *et. al.*, 1993). Obtaining accurate, quantitative mass balances for waste addition and removal are much more difficult in open water systems since hydrographic conditions, natural and analytical variability, and seasonal changes in fish physiology make it difficult to isolate changes in water quality due to aquaculture. A more simplistic a approach would be to calculate the amount of nitrogen discharged to system from finfish operations, and the amount of nitrogen extracted by plants or bivalves in harvested biomass. In 1999, the University of New Hampshire established a 30-acre aquaculture demonstration site 8 km from shore in the open waters of the Gulf of Maine (Fig. 3). The site located in 52 m of water and is fully exposed to wind and tides from all directions. Wave heights can reach 9 m in severe storms.

Aquaculture installations at the site include two submersible fish cages and two submerged longlines for bivalve mollusc culture. While the project was not intentionally established to demonstrate integrated aquaculture, the presence of finfish and bivalve molluscs provided an opportunity to investigate the capacity of the molluscs to mitigate nitrogen wastes resulting from finfish production.

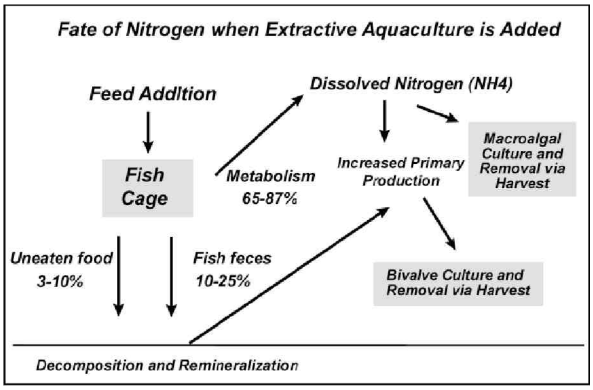

Fig. 2. Pathway of nitrogen wastes in integrated aquaculture systems

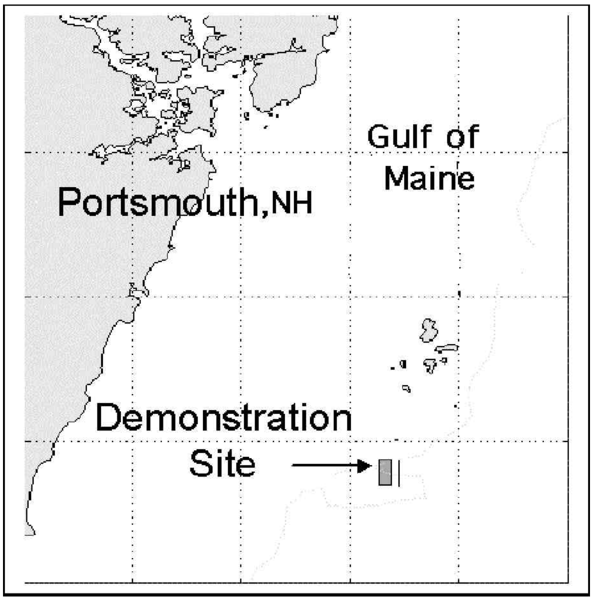

Fig. 3. Map of the New Hampshire and Southern Maine coast showing the location of the open ocean aquaculture demonstration site. The rectangle represents the area in which the fish cages are moored and the adjacent line represents the longlines used for bivalve mollusc culture.

Materials and Methods

Fish and shellfish were cultured in adjacent installations consisting of two submerged sea cages and two submerged longlines. The sea cages were Ocean Spar Technologies, Inc, 600 m^3 Sea Stations, one of which was modified for flatfish culture (Fig. 4). The sea cages occupy a rectangular area of seafloor 24 acres in size, with the length of the rectangle oriented north to south (Fig. 3). The shellfish longlines are located approximately 200 m to the east of the sea cages, and together are 360 m in length. In the current operations, the cages are stocked with 1,500 Atlantic halibut (*Hippoglossoides platessoides*) and 4,000 haddock (*Melanogrammus aeglifinis*) respectively. A proposed expansion of finfish production includes the addition of a third larger cage (3,000 m^3) in 2003 that will be stocked with 37,500 Atlantic cod (*Gadus morhua*). The increased production plan also includes increasing the stocking density of the smaller cages to 25 kg/m^3, which would bring the numbers of halibut and haddock up to 3,750 and 7,500 respectively.

The growout perid for halibut from a 100 gm stocking size to 4 kg is 36 months. Under current stocking density, this would result in total production at harvest of 6,000 kg for the cage. Haddock are grown to 2 kg each in 24 months, yielding a harvest of 8,000 kg.

The amount of nitrogen discharged from finfish operations has been estimated in a number of studies, and most of these have focused on salmon production. The vast majority (87 %) of discharged nitrogen is in the dissolved inorganic form consisting of ammonium (80 %) and nitrate-nitrite (20 %) (Sowles and Churchill, 2002). The estimates range from a low of 30 kg annually per ton of fish, to a high of 78 kg (Sowles and Churchill, 2002). The higher figures were calculated in the early 1990's (Enell and Ackfors, 1991) and the lower discharge estimates in subsequent studies likely reflect improved efficiencies in feed formulation and husbandry practices (Sowles and Churchill, 2002). For this study, an annual value of 50 kg N per ton of fish was used.

The amount of nitrogen removed annually via bivalve harvest was calculated by multiplying the total annual production in meat weight times the percent nitrogen of mussel flesh. At full capacity, each longline can yield 6,000 kg live weight of mussels in a 12 month growout period, resulting in annual production of 12,000 kg whole live weight. Meat yields of mussels cultured at the site have ranged seasonally from 42 % to 60 % with an average of 50 % throughout the year. Estimates of nitrogen content of bivalve flesh range from 1.3 % to 1.8 % (Rice, 2001). A figure of 1.6 % was used in this study.

Since the growout period for halibut is three years, a three-year cycle was used in calculating discharge and extraction. Fish weights and total tonnage from each cage per year was based on observed growth rates for this project (Howell, unpublished data). For halibut, average individual weights of 0.5 kg, 2 kg, and 4 kg were used for years 1, 2 and 3 respectively. For haddock, average annual weights of 0.5 kg and 2 kg were used for years 1 and 2. Year 1 of a second haddock growout cycle was used to calculate the total production weight for year 3. No mortality for either halibut or haddock was assumed in calculating nitrogen discharge. Total weight of mussel meat (and nitrogen removed) was based on observed production and meat yield data from this project (Langan, 2001). Meat yields range throughout the annual growout cycle from a low of 42 % to a high of 60 %. An average meat yield of 50 % was applied to the annual production of 12,000

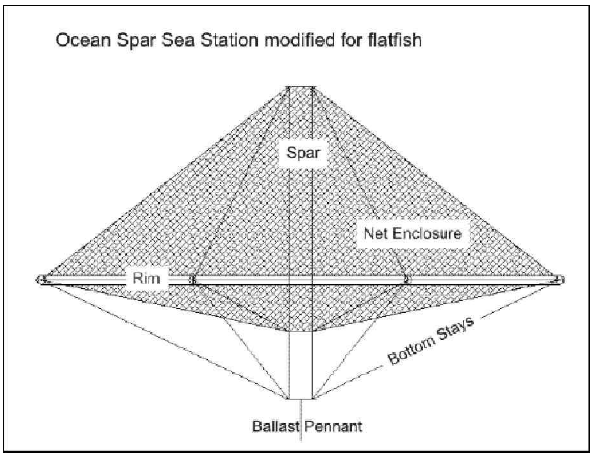

Fig. 4. A schematic of the 600 m^3 OST Sea Station cages used for finfish growout. The cage in this diagram was modified for flatfish culture.

kg whole live weight. Discharge and extraction for the current fish and mussel production (described above) and for the proposed finfish expansion were calculated.

Results

Total estimated nitrogen discharge for the two sea cages is presented in Table 1. For the three-year period, production of 6,000 kg of halibut resulted in a discharge of 488 kg of nitrogen. Haddock production, which was estimated at an 8,000 kg harvest in year 2, followed by a restocking with 4,000 juvenile fish in year 3, resulted in an estimated discharge of 600 kg of nitrogen, bringing the three year total for both species to 1,088 kg of nitrogen.

Nitrogen extraction via mussel harvest as-

Table 1. Calculation of total nitrogen discharge for a three year period for two cages. Wt/fish=the average weight of individual fish at the end of the production year, Biomass=total biomass in the cage at the end of the production year

Species	Year	No.	wt/fish	Biomass	N/ton	N dis
Halibut	1	1500	0.5kg	750kg	50kg	38kg
	2	1500	2.0kg	3,000kg	50kg	150kg
	3	1500	4.0kg	6,000kg	50kg	300kg
Halibut total						488kg
Haddock	1	4000	0.5kg	2,000kg	50kg	100kg
	2	4000	2.0kg	8,000kg	50kg	400kg
	3	4000	0.5kg	2,000kg	50kg	100kg
Haddock total						600kg
Two cage total nitrogen discharge						1,088kg

Table 2. Calculation of the amount of nitrogen extracted via mussel harvest over a three-year period. Total wt=total live weight of mussels and shell, MY=meat yield, MW=meat weight

Year	Total wt	MY	MW	%N	kg N
1	12,000kg	50%	6,000kg	1.6	96kg
2	12,000kg	50%	6,000kg	1.6	96kg
3	12,000kg	50%	6,000kg	1.6	96kg
Total nitrogen extracted					288kg

Table 3. Calculation of total nitrogen discharge for a three year period from three fully stocked cages

Species	Year No.	wt/fish	biomass	N/ton	N dis	
Halibut	1	3750	0.5kg	1,875kg	50kg	94kg
	2	3750	2.0kg	7,500kg	50kg	375kg
	3	3750	4.0kg	15.000kg	50kg	750kg
Halibut total						1,219kg
Haddock	1	7500	0.5kg	3,750kg	50kg	188kg
	2	7500	2.0kg	15,000kg	50kg	750kg
	3	7500	0.5kg	3,750kg	50kg	188kg
Haddock total						1,126kg
Cod	1	37500	0.5kg	18,750kg	50kg	938kg
	2	37500	2.0kg	75,000kg	50kg	3,750kg
	3	37500	0.5kg	18,750kg	50kg	938kg
Cod total						5,626kg
Three cage total nitrogen discharge						7,971kg

sumed three complete growout cycles at the full production capacity of 12,000 kg/year. These calculations are presented in Table 2. For the current operations at the site, which consists of low stocking densities for the two cages, total nitrogen discharge exceeds nitrogen extraction via mussel harvest by 800 kg over a three-year period. Therefore, in order to remove all the nitrogen discharged from finfish production, mussel production would have to be increased by a factor of 2.7, or to 32,400 kg/year. Increasing production to this level would require the installation of six additional longlines.

Similar calculations for nitrogen discharge were applied to the proposed expansion of finfish production and are presented in Table 3. The expansion includes fully stocking the 600 m^3 Sea Station cages to a 25 kg/m^3 density with haddock and halibut, and the addition of a 3,000 m^3 cage with Atlantic cod at the same stocking density. Cod have a two-year growout cycle and annual biomass for year 3 was treated similarly to haddock production in the previous example.

If three cages are fully stocked for growout, the total nitrogen discharged to the environment over a three-year period would be 7,971 kg, or 2,657 kg per year. Based on the calculations presented in Table 2,125 kg of mussels (live weight) need to be harvested to extract 1 kg of nitrogen. Therefore, if a goal for the proposed expansion of finfish production was no net addition of nitrogen, 332,125kg of mussels would need to harvested each year to extract all the nitrogen added by finfish culture.

Discussion

Based on the results of presented here, balancing the total nitrogen discharge from finfish culture operations by integrating extractive species such as bivalves would require the scale of operations for the extractive species to be far larger than the finfish operations. Certainly from an industry perspective, this would create operational management complexity as well as a significant challenge for marketing the large volume of extractive product. The exercise of making these calculations was undertaken to investigate the capacity for mitigating nitrogen addition by culturing an extractive species such as mussels, and is by no means to be construed as advocacy for no net addition of nitrogen for all culture operations. The location of the culture site, the trophic condition and assimilative capacity of the receiving waters, and marketing landscape must all be taken into consideration in order to determine the most effective approach to integrated aquaculture. In locations such as the Gulf of Maine where this project is being conducted, the coastal waters are naturally high in nitrogen due to upwelling of deep nutrient rich waters. It is highly unlikely that operations in offshore environments with high ambient nitrogen concentrations and large dilution capacity would be impacted by discharge from finfish culture. Sowles and Churchill (2002) investigated the potential exposure and effect of nutrient enrichment by salmon culture in Cobscook Bay, Maine, U.S.A. They found that despite the significant loading associated with annual production of 6,000,000 kg of salmon, there was little change in water column nitrogen concentration and no discernable increase in primary production. Similarly, Wildish *et al.* (1992) reported difficulty measuring differences in nitrogen concentration from ambient conditions beyond a few meters from the cages in an intensely farmed area of the Bay of Fundy. Whether or not nitrogen plumes above ambient conditions can be measured should not be the only criteria for determining whether finfish operations should be permitted, or mitigation by extractive species should be required. Determining the assimilative capacity and nutrient sensitivity of the surrounding waters is extremely important (Chopin *et al.*, 2001). In some cases, an increase in nutrient loading may result in beneficial increases in secondary production without any associated negative impacts. Nixon and Buckley (2002) examined nutrient loading in relation to fisheries growth and biomass data from the Baltic Sea. They found that fish growth and biomass were significantly greater with increased nitrogen loading in the latter throughout the 20th century. Concerns over nutrient additions to coastal waters are in many cases valid, however, it should be recognized that nutrients are essential for producing biomass, and may potentially result in greater fisheries yields. Certainly, if aquaculture operations are to be sited in waters that are already eutrophic or have been scientifically determined to be nitrogen sensitive, they should be of the extractive type or at minimum strive to balance inputs with removal.

As illustrated by the exercise undertaken in this study, if no net increase in nitrogen is a goal for aquaculture development, it would be difficult to achieve without shifting the emphasis from finfish to extractive species such as bivalves and seaweeds, or by vastly reducing discharge by improving feed formulations and nitrogen assimilation by the fish. Nutrient issues aside, there may be other reasons for a more integrated approach to aquaculture development. Among these are to counter the negative perception of aquaculture by the environmental and regulatory communities, to increase profit margins with revenue from secondary crops and to reduce the financial risk of relying on a single species.

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References

Chopin T., Bushmann A. H., Halling C., Troell M., Kautsky N., Neori A., Kraemer G. P., Zertuche-Gonzalez J. A., Yarish C., and Neefus C., 2001: Integrating seaweeds into marine aquaculture systems: a key toward sustainability. *J. Phycol.*, **37**, 975-986.

Enell M., Ackfors H., 1991: Nutrient discharges from aquaculture operations in Nordic countries into adjacent sea areas, ICES Council meeting Papers, ICES CM 1991/f. International Council for the Exploration of the Sea, Copenhagen, 56pp.

FAO. 2000: The State of World Fisheries and Aquaculture 2000, UN Food and Agriculture Organization, document number, ISBN 92-5-104492-9.

Goldberg R., and Triplett T., 1997: Murky Waters: Environmental Effects of Aquaculture in the United States, Environmental Defense Fund Publications.

Langan R., 2001: Annual Report for the UNH Open Ocean Aquaculture Demonstration Project, NOAA technical report # NA06RP0454.

McVey J. P., Stickney R. R., Yarish C., and Chopin T., 2002: Aquatic Polyculture and balanced Ecosystem management: new paradigms for seafood Production, in "Responsible Marine Aquaculture" (eds. by Stickney R. R. and McVey J. P.), CABI, Oxon, UK., pp.91-104.

Nixon S.W., Buckley B.A., 2002: "A Strikingly Rich Zone"- Nutrient Enrichment and Secondary Production I Coastal marine Ecosystems. *Estuaries*, **25(4b)**, 782-796.

Rice M. A., 2001: Environmental impacts of on-bottom shellfish culture and natural bivalve populations, in "Proceedings of the Alaska on-bottom shellfish aquaculture workshop" (ed. by LaRonde R.), Alaska Sea Grant, pp.13-14.

Shpigel M., Neori A., Popper D.M., and Gordon H., 1993: A proposed model for "environmentally clean" land-based culture of fish, bivalves, and seaweeds. *Aquaculture*, **117**, 115-128.

Sowles J. W., L Churchill., 2002: Potential Exposure and effects from nutrient enrichment by salmon aquaculture in Cobscook Bay, (MS in preparation)

Wildish D. J., Keizer P. D., Wilson A. J., and Martin J. L., 1993: Seasonal changes of dissolved oxygen and plant nutrients in seawater near salmonid net pens in the macrotidal Bay of Fundy. *Ca. J. Fish. Aquat. Sci.*, **50**, 303-311.