
CHAPTER 6

ENVIRONMENTAL ISSUES ASSOCIATED WITH OFFSHORE AQUACULTURE & MODELING POTENTIAL IMPACT

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ABSTRACT

Real and perceived aquaculture environmental impacts that must be considered prior to expansion to open ocean locations include: 1) benthic carbon loading, 2) water column nitrification, 3) stimulation of harmful algal blooms, and 4) escapement and implications to wild populations. A simulation model was developed for predicting the benthic impacts from offshore cage culture. The model simulates the impact of feed and feces from one cage on a 600 m² area on the seafloor using total organic carbon (TOC) as an indicator. A Gaussian error was added to all variable means to represent variation about central tendencies. Cobia, red snapper, and red drum were the cultured species. We also considered depths of 20, 40, and 60 m between feces and feed point of release from the cage and the seafloor. Variables associated with management scenarios and fish biology were held constant throughout simulation runs. Cobia culture resulted in the least impact on TOC accumulation. Cages operated at 40 m depth resulted in 20% less TOC accumulation than those operated at 20 m. Operations at 60 m resulted in an accumulation of TOC of over 60% less of that from 40 m. Additional research is necessary to validate model results with data collected from operating open ocean aquaculture ventures prior to industry usage of the simulation model for site selection and management planning purposes.

INTRODUCTION

Cage culture is practiced in coastal bays, fjords, and lochs in numerous countries throughout the world. Due to increasing seafood demand and coastal expansion bottlenecks, coastal aquaculture areas are becoming increasingly burdened. To alleviate space constraints, cage aquaculture has been recently pressured to move offshore for grow-out. Limits to coastal expansion, additionally, are associated with potential environmental impacts by aquaculture. Some environmental impacts might be minimized by operating in more exposed locations, adding to the pressure for cage aquaculture to move to open and deeper sites.

No aquaculture industry presently exists offshore in U.S. federal waters within the United States Exclusive Economic Zone (EEZ). Introducing a new use for the offshore EEZ presents significant challenges for appropriate aquaculture site selection. Numerous users of the EEZ are established, including the commercial and recreational fishing industry, the oil and gas industry (minerals rights and future exploration), shipping (established channels), military zones (national defense and training), and dumping zones. Existing uses potentially limit access to appropriate

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grow-out sites, especially when considering the environmental and oceanographic criteria for optimal sites. Additionally, offshore aquaculture sites may also have production limits prior to negatively impacting the environment, thereby decreasing economic potential to investors.

ENVIRONMENTAL IMPACTS FROM OFFSHORE AQUACULTURE

Real and perceived aquaculture environmental impacts that must be considered prior to expansion to open ocean locations include: 1) benthic carbon loading, 2) water column nitrification, 3) stimulation of harmful algal blooms, and 4) escapement and implications to wild populations. Adoption of a thorough site selection process and suitable technologies that minimize effects will relieve many concerns related to environmental impacts.

Benthic impacts associated with waste solids accumulation can be attributed to poor site selection, management decisions, site overproduction, or some combination of these. Numerous studies throughout the world have documented the benthic impact associated with fish farming (Table 1; from Costa-Pierce and Bridger 2002). Most of the studies in Table 1 monitored environmental impacts associated with near shore and protected aquaculture sites. Owing to greater residual current, potentially deeper water, and greater assimilative capacity in open ocean conditions (Gowen and Edwards 1990), benthic impacts from exposed aquaculture operations are anticipated to be less than comparable sized near shore operations. Having decreased impact allows for larger size farms with more fish for grow-out. However, even exposed aquaculture sites would eventually reach an assimilative carrying capacity that could result

in harm to the environment, if nutrient inputs exceed an acceptable threshold. Two reports of monitoring open ocean aquaculture sites in the U.S. have provided no evidence of benthic impact from open ocean operations (Bybee and Bailey-Brock 2003; Grizzle et al. 2003). Bybee and Bailey-Brock (2003) further illustrated the results of optimizing farm practices during the development phase of the project with comparable results observed over two consecutive years despite doubling fish density and feed. However, caution should be taken when interpreting these results as neither study may be indicative of actual results that would be attained from commercial operations. Only after monitoring commercial fish farming efforts in the open ocean can more accurate conclusions be drawn regarding benthic impact from exposed site applications.

Water quality impacts are mostly related to the addition of nutrients from feeding and fish excretion. Introduction of excess nutrients, particularly dissolved inorganic nitrogen, in the marine environment may result in algal blooms that can deleteriously affect aquaculture (discussed later in this section). Increased nutrient loading will also result in eventual depletion of oxygen in the surrounding water. This could increase stress in the cultured stock and result in fish health deterioration to arise with subsequent mortality leading to devastating economic losses. In exposed open ocean conditions, rapid removal of farm wastes and large volumes of water passing through a farm site resulting in large dilution of wastes will likely mitigate effects on water quality. However, open ocean farms will exist at enormous operational scale, thereby resulting in much larger quantities of dissolved nutrients into the environment, warranting extensive environmental monitoring programs.

Table 1. Degree of benthic 'halo' region impact associated with aquaculture operations.

Study	Benthic Impacts Reported
Mattsson and Linden (1983)	Species composition changed up to 20 m away from mussel farm
Brown et al. (1987)	Species composition changed up to 15 m away from cage edge
Gowen et al. (1988)	Species composition changed up to 30-40 m away from cages
Lumb (1989)	Impacts restricted to within 50 m of cage edges and dependent on seabed type
Ritz et al. (1989)	Macrofaunal community under the farm adopted an undisturbed condition 7 wk post-harvest of farm stock
Kupka-Hansen et al. (1991)	Species composition changed up to 25 m away from cages
Weston (1990)	Farm effects on sediment chemistry evident up to 45 m from the farm; species composition changed at least to 150 m away from cages
Johannessen et al. (1994)	No influence of fish farming could be detected 250 m away from cages
Krost et al. (1994)	Affected area extended 3-5 m from the fish farm margin
Wu et al. (1994)	Impacted area extended to 1000 m with industry using trash fish as feed and poor water flushing exists
McGhie et al. (2000)	Farm wastes largely restricted to area beneath sea cages; most of the sediment organic input from feces; and 12-month following period sufficient to return site to pre-farm oxic conditions
Morrisey et al. (2000)	Large temporal & spatial variabilities depending on water velocities; recovery times estimated between 3-12 years
Dominguez et al. (2001)	No affect on physical and chemical sediment characteristics due to fish farm operation in high average water current velocity (6 cm/s) site.

Further deterioration of water quality can result from extreme loading to the benthic environment, which could result in production of hydrogen sulphide affecting fish health and performance of the farm. Such a situation might occur in coastal aquaculture sites that have low rates of flushing and high farm waste deposition. Comparable situations are unlikely in more exposed locations, although farm operators need to be aware of this possibility given the large scale of operation expected offshore. Hydrogen sulphide effects to farm stock may be minimized by siting cages in locations that allow a water depth in excess of 10 m between the bottom of the cage and seabed at low tide (Gowen and Edwards 1990). This depth allows sufficient exposure of the gas bubbles to the water column to oxidize the hydrogen sulphide gas, removing its toxicity.

Fish farming will result in increased nutrients in the surrounding environment. However, most studies to date have concluded

that aquaculture sited in preferable locations for optimal fish health will not result in increased abundance of phytoplankton species (Parsons et al. 1990; Pridmore and Rutherford 1992). In fact, Arzul et al. (2001) reported inhibited phytoplankton growth when in the presence of excretion from selected finfish species (sea bass and salmon). These results were in stark contrast to the excretion from shellfish species (oysters and mussels), which stimulated phytoplankton growth rates.

Aquaculture escapees have been cited to demonstrate ecological, disease and genetic interactions with wild fish stocks in the vicinity of the aquaculture operations. Escapees are also particularly troublesome to the aquaculture entrepreneur as they represent a loss of stock value from the farm. Myrick (2002) discussed escapement of cultured species while Bridger and Garber (2002) specifically reviewed the salmonid escapement occurrence, implications, and solutions for mitiga-

tion. Salmonid escapees—specifically steelhead trout—have been observed to remain in the vicinity of aquaculture cages following escapement to the wild and displayed a homing response to aquaculture facilities if escapement occurred away from established aquaculture sites (Bridger et al. 2001). These results indicate a much lower risk from escapement to wild stocks than portrayed by environmental NGOs. Further, using biological cues to attract escapees allows development of recapture strategies to return escapees to cages for additional growth and decrease economic losses possible. Genetic impacts from escapees are considered an issue within salmon populations because of the species having geographically isolated populations within individual river systems that can be negatively impacted through the introduction of exotic genetic material. Cobia, red snapper, and red drum are all genetically considered panmixic and therefore regulated as one genetic stock throughout a fishery region. This population structure differs considerably from the salmonid case and greatly reduces the potential impact of genetic pollution from aquaculture escapees. Regardless, the most logical approach to mitigate impacts of escaped aquaculture fish is prevention. Appropriately designed aquaculture cages that can sustain the oceanographic loads anticipated in the open ocean will lower the probability for escapement.

PREDICTING BENTHIC IMPACT

Benthic impacts from feed and fish feces may be a function of site selection, management decisions, and site overproduction. Offshore aquaculture site selection and overproduction might be assessed by using numerical models, as is done in other fields, such as engineering, weather prediction, or economics. Numerical models might become a cor-

nerstone in aquaculture to determine environmental impacts and farm siting. The incorporation of environmental impact assessment models, however, will fall largely on the extension community to provide the technology transfer to the new industry.

Numerous authors have discussed the mechanics and relationships involved in modeling benthic impacts from fish farm wastes (e.g., Hargrave 1994). Complex hydrodynamic models have been developed for specific regions (Panchang et al. 1997), but are unlikely to be general. DEPOMOD is a more generic, end-user benthic impact model developed for the Scottish cage culture industry (Cromey et al. 2002) using changes in species population composition to determine impacts. Although generic to the sea loch systems in Scotland, DEPOMOD may have limitations for its use in siting farm operations and management in the open ocean and outside Scotland. The Simulation for Environmental Impact (SEI) model used in this study was created to provide a tool that can be integrated into the development of an offshore aquaculture industry for appropriate site selection, optimal environmental management decisions, and application of medicated feed in exposed or offshore environments (Riedel and Bridger 2003).

THE SIMULATION FOR ENVIRONMENTAL IMPACT

SEI is intended to be a tool for the offshore aquaculture industry to help determine best farm locations (based upon oceanographic conditions) and stations for environmental monitoring of farm-related impact. SEI may also aid in determining more efficient farm management practices. Specific objectives for developing SEI were to:

1. predict potential environmental impacts measured by benthic carbon loading associated with various environmental and fish farm management scenarios;
2. develop a graphical user interface tool that extension professionals may use to assist the industry in determining off-shore aquaculture sites and management strategies to minimize detrimental environmental impacts; and,
3. provide the industry with advanced statistical diagnostic tools to assist with environmental monitoring and potential future diversification of activities, such as application of medicated feed.

Although SEI is intended to use TOC to indicate impact, other impact metrics may also be used depending upon the exact reason for using SEI, such as other chemical compounds or indices for species health or diversity. In Scotland, mathematical models have been accepted by regulatory agencies for farm site selection and monitoring medicated discharges from cage operations (Singleton and Rosie 2003). We, however, advise against relying solely on SEI to make regulatory and critical management decisions.

SEI has the look and feel of most Windows-based commercial software packages in that it consists of a menu-driven window with dialog boxes (Fig. 1). SEI is user friendly and has a visual interface to aid in exploring and interpreting various fish farm management scenarios. It also allows more complex spatial analyses through output of a text file ready to be imported into most data analysis software.

MODEL DESCRIPTION

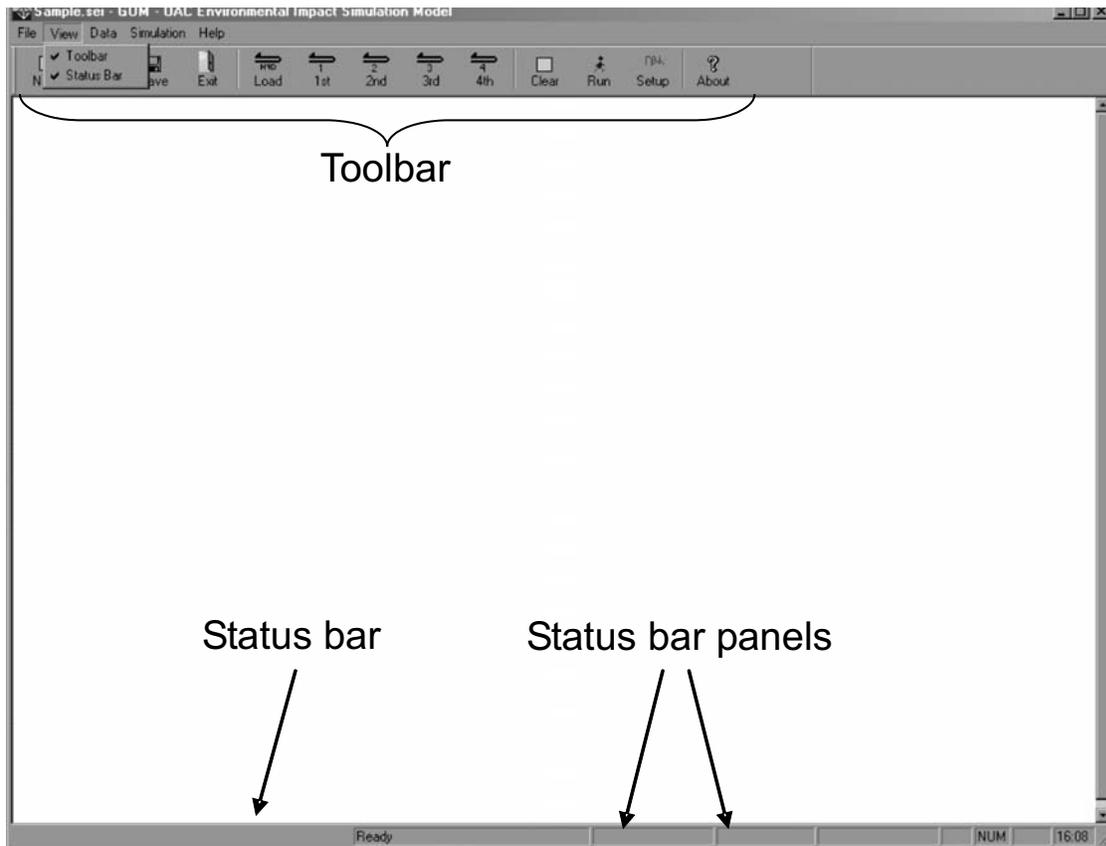
SEI was designed to simulate the fate of individual feces and feed pellets (referred to as pellets hereto forth) after their exit to the open water from the physical bounds of a fish cage. SEI simulates each pellet individually during one day for the duration of up to a year. Simulating individual pellets makes the program more realistic than approaches dealing with average pellets over extended time periods. While this approach is more realistic it also increases the computational complexity of the model and time required to process the fate of all pellets exiting the fish cage.

The underlying model in SEI is based upon a suite of variables that represent processes within the cage, in the open water, and in the sediment (Fig. 2). In the end, SEI only simulates the effects of pellets exiting the cage on the sediment.

SEI simulations are based on uniform and Gaussian random numbers. Computer routines may be executed many times during each simulation due to the potentially high number of pellets released by the simulated fish cage. To minimize sequential autocorrelations, SEI avoids linear congruential methods (Devroye 1986; Knuth 1997) for generating random numbers, compromising speed in favor of accuracy.

All estimates of spread around mean values of the variables in SEI are assumed normally distributed. Uniform deviates for generating normal deviates follow the algorithm by Park and Miller (Press et al. 1997). The period of that algorithm is estimated at approximately 2.1×10^9 , which is below the number of random values we generated in any simulation scenario. Generation of normal random

Fig. 1. The SEI program has the look and feel of most Windows-based commercial software packages in that it consists of a menu-driven window with dialog boxes.



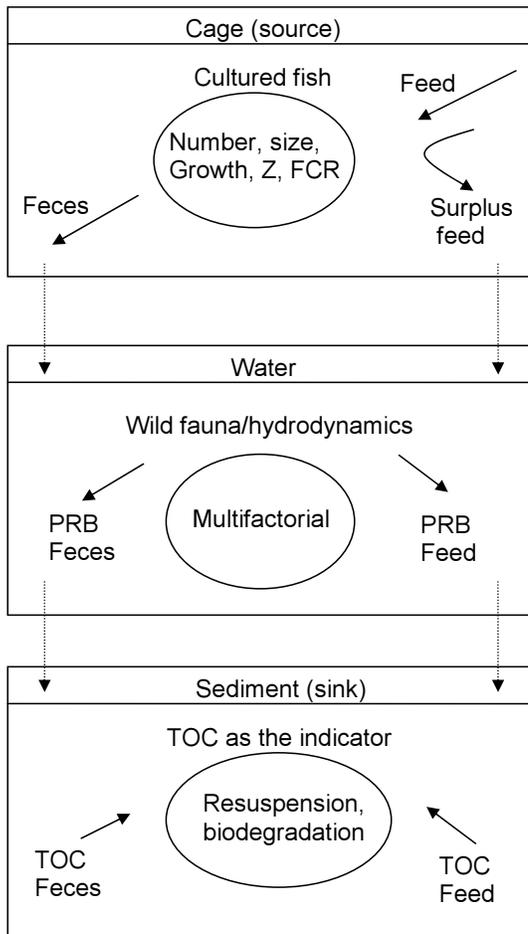
deviates followed the algorithm developed by Box and Muller (Bratley et al. 1987).

Variables within SEI for calculating the number of pellets leaving the cage into the open ocean reflect fish biomass and the management practices of the farm. The fish density per cage, fish average monthly weight, and fish mortality estimates fish biomass. Biomass, in turn, will affect fish feces production and wasted feed, which are the only factors in SEI contributing to sediment total organic carbon (TOC) accumulation. Fish mortality is estimated by a negative exponential function (Ricker 1975). Fish feces produc-

tion is estimated according to Findlay and Watling (1994) and wasted feed according to Silvert (1994).

SEI uses local hydrology data, pellet settling speed, and the probability of pellets reaching the sediment to simulate the fate of pellets between the cage and the ocean floor. Hydrology data are ocean current speed and direction for the time the pellet is settling to the bottom. That time is determined from data on pellet settling speed and depth of the farm site. Hydrology data also includes the coefficient of variation for both current speed and direction. The coefficient of variation is used

Fig. 2. Simulation for Environmental Impact model components and driving variables of processes determining total organic carbon accumulation on sediment below a fish cage.



for adding a random component to the current acting on the settling pellet.

TOC in the top 5 cm of sediment is the impact indicator used within SEI. We used a 600 x 600 m impact grid because over 95 % of the pellets land on that area, given the hydrodynamic characteristics of our test site. To compromise accuracy and simulation time, we used a 1 m² patch (grid cell) on the impact grid as the minimum area of impact.

Once the pellet is on the bottom, SEI indirectly estimates pellet attrition due to resuspension or consumption. Attrition estimates are calculated as the TOC ratio between values from the previous and present months. The ratio is used to adjust impact downward. As an example, if the TOC ratio between the previous and present month is 2 (previous month with twice TOC), the estimated impact from pellets is adjusted to half. No adjustments are made if the ratio is one or smaller.

SEI considers sediment type by using the weight of a patch of sediment 1 m² x 5 cm. Weight was used as a surrogate for sediment compaction and fractionation. High weights imply compact sediments, which is less sensitive to the weight of an incoming settling pellet.

Accumulation of TOC in the sediment is calculated by SEI when the sediment TOC is less than the TOC in the pellet. Conversely, a decrease in sediment TOC is calculated when the sediment TOC is above that of the pellet. Accumulation of total organic carbon on sediment is modeled with the second-order equation:

$$y = \text{TOC}_{\max} * (1 - e^{(K*W)})$$

where TOC_{\max} is the asymptotic TOC value (maximum of sediment, feces, and pellet TOC values), K is the curve steepness (weight of TOC from pellet / weight of TOC in sediment), and W is the weight of pellet units fallen on that specific grid cell.

Attrition of TOC from the sediment is modeled using the exponential decay model:

$$y = e^{-W}$$

where W is as above.

SIMULATION SCENARIOS AND DRIVING VARIABLES

We chose a simulation reference site that was comparable to the Offshore Aquaculture Consortium (OAC) research site off Mississippi. The simulation reference site was located near a gas platform 40 km offshore. Simulation data for farm management were informed by economic modeling results presented by Posadas and Bridger (this volume). Posadas and Bridger (this volume) investigated the economic feasibility of offshore aquaculture in the northern Gulf of Mexico with cobia, red snapper, and red drum serving as likely candidate species. Cobia had an anticipated growth rate of 729 g/mo and an initial stocking density of 6 fish/m³; red snapper had an anticipated growth rate of 46 g/mo and an initial stocking density of 67 fish/m³; and, red drum had an anticipated growth rate of 100 g/mo and an initial stocking density of 33 fish/m³. All three scenarios using 12–3,000 m³ cages proved to be economically feasible and were, therefore, used in our simulations. We also added an estimate of 20% mortality to determine fish losses occurring at a fish farm and a starting stocking size of 10 g for all species (Posadas and Bridger, this volume).

We considered the feed and feces leaving the cage to be the only source for impact on the sediment. The driving variables within the cage were average weight for a month of an individual fish, fish number in a cage, and food conversion ratio. Food conversion ratio was used to determine the amount of feed lost from the cage (Silvert 1994). The driving variables within the open water compartment were current speed and direction, and water depth. Current speed and direction were obtained from the National Ocean Service for 2001 at a reference site in the vicinity of the OAC research site. The coefficients of varia-

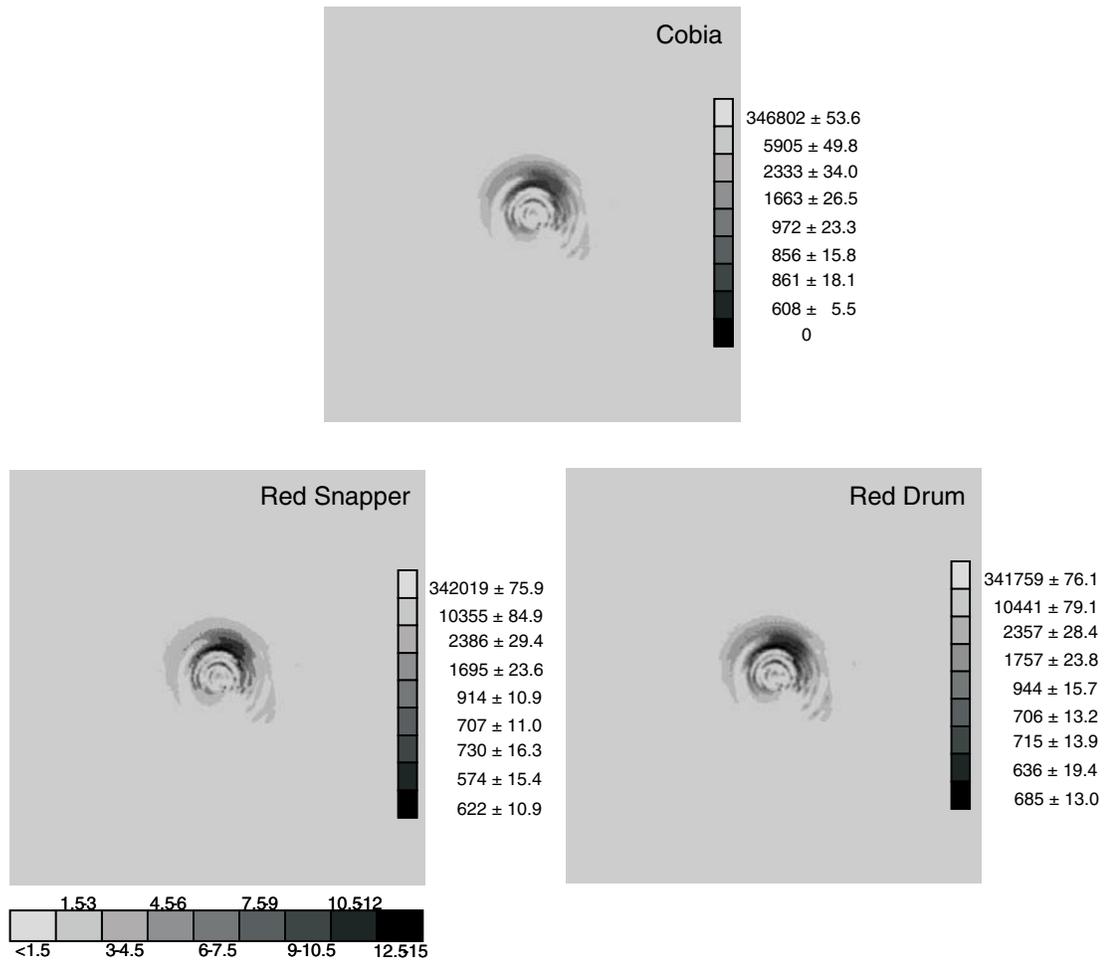
tion for current speed and direction were calculated from direct measurements with a current meter from our site during January and July 2001. Variation was obtained from thirty current speed and direction readings one minute apart at 5 m depth. The likelihood for the feed pellets to reach the bottom was set to 0.1 and for the feces pellet to 0.04 (Findlay and Watling 1994). The amount of feed given was fixed at 4% body weight, settling speed for feces was 10 cm/s and for feed pellets was 7.5 cm/s (Chen et al. 1999), and feces TOC was fixed at 12% and feed TOC was fixed at 15%. Sediment TOC was fixed at 0.9% and the weight of a 1 m² x 5 cm parcel was fixed at 150 kg. Grow-out times were nine months for cobia (March to December), and twelve months for red snapper and red drum (Posadas and Bridger, this volume).

ANALYTICAL APPROACH

Model output data was analyzed for the three species scenarios independently using ordinary kriging to represent TOC magnitude and extent on the impact grid. A spherical semi-variogram model was applied because it best fit the error structure of the data. An anisotropic model was also applied because of the presence of a directional component in the water circulation data for the year 2001 at our simulated location. To allow for visualization, TOC values were categorized into ranges. Nine equal sized ranges represented TOC values between 0 and 15.

To keep the scenarios comparable among species, simulations for cobia during an entire year was used but the impact was adjusted at each grid cell to 75% of that for the entire year. This adjustment was to correct the year-long simulation results to the expected nine month period (March–December) for cobia

Fig. 3. Effects of species farmed on the total organic carbon accumulation below a 3000 m³ cage. Numbers down the scale bars are mean area (m²) ± one standard deviation.



grow-out. The model was run over the twelve months to keep the circulation patterns identical among the cultured species.

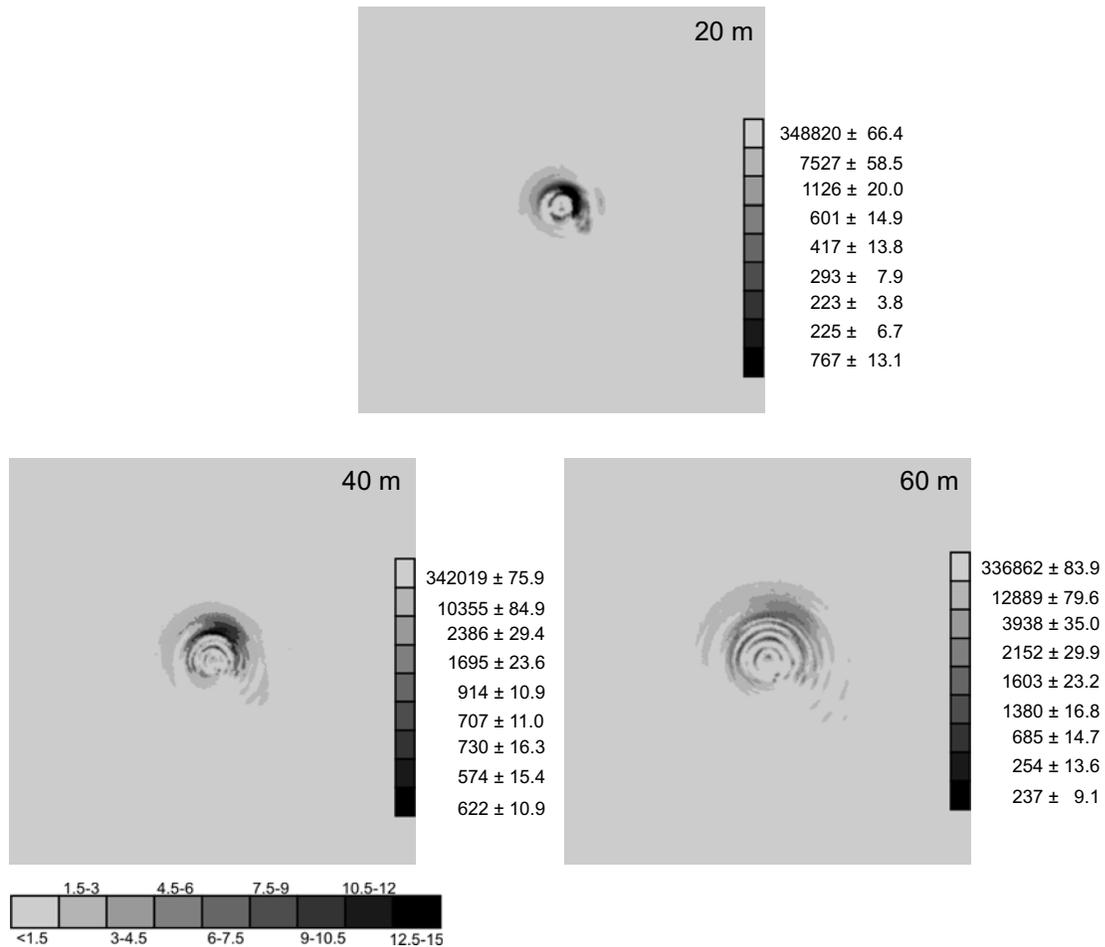
RESULTS

The maximum possible TOC level, the TOC level at saturation, given the simulation data above is 15% (maximum among TOC sources). Lytle and Lytle (1982) report TOC levels of highly polluted areas in the

Mississippi Sound of 10% and above. The level of TOC from our maximum range may, therefore, be considered environmentally detrimental.

Cobia produced the least impact among the three species, followed by red snapper, and red drum (Fig. 3). Red snapper and red drum had comparable effects on sediment TOC, even though the growth rate for red drum was twice that from red snapper. The area above 12% TOC for red drum was less

Fig. 4. Effect of depth on the total organic carbon accumulation on sediment below a red snapper 3000 m³ cage. Numbers down the scale bars are mean area (m²) ± one standard deviation.



than 1%, being possibly environmentally sustainable at the simulated depth.

The effect of depth on TOC accumulation demonstrates the potential for open ocean cage culture when environmental effects from that activity are detrimental in coastal areas. Our simulated results illustrated a 20% reduction in the TOC area above 12% when running the simulation from 20 to 40 m. We, however, observed a 62% reduction when running the simulation from 40 to 60 m (Fig. 4). Open ocean areas adequate for cage culture may be

in deeper than 60 m, which may further assure that environmental impacts of that activity may be minimal when in deep, open ocean sites.

CONCLUSIONS

Environmental impacts from cage culture may include benthic carbon loading, water column nitrification, and stimulation of algal blooms. We only considered accumulation of TOC, which is a surrogate for a broad range of

possible effects. A potential way to reduce the impacts of TOC accumulation on sediment, aside from site selection, is fallowing. When the impacts of multiple cages become environmentally unsustainable, one may consider setting aside a farm site for the duration of several months to a year. Appropriate site selection coupled with fallowing, particularly with respect to depth, may enable farms to operate in areas small enough to avoid user conflicts, yet have an enough number of cages to be profitable.

Benthic impacts from feed and fish feces are a function of site selection, management decisions, and site overproduction, which are variables not well understood in the yet incipient industry of cage culture in the offshore environment. The use of environmental impact assessment models may shed light into those variables to assure that the offshore cage culture industry is able to cohabit with all other industry sectors exploiting ocean resources. The incorporation of such models will initially fall largely on the extension community to provide the technology transfer and necessary advice to the new industry. Appropriate site selection and optimal environmental management decisions are essential to keep offshore cage culture a viable option for fish production. Models such as the one presented here are tools for making unbiased and effective decisions toward that goal. Additional research is necessary to validate model results with data collected from operating open ocean aquaculture ventures prior to industry usage of the simulation model for site selection and management planning purposes.

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