CHAPTER 3

THE EFFECT OF BENTHIC CARBON LOADING ON THE DEGRADATION OF BOTTOM CONDITIONS UNDER FARM SITES

by

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ABSTRACT

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Twenty-three fish pen systems in Maine have been studied, and benthic conditions under these systems have been evaluated. A model has been developed to evaluate the amount of carbon accumulation and benthic deterioration under fish farms. An important feature of the model is that it deals with the dynamics of the interaction between the farm and the benthos and shows how bottom conditions change over time. There is a high degree of agreement between the predictions of the model and the field data. The model appears to provide a quantitatively useful tool to managers and regulators alike for estimating the potential benthic impacts of fish farming.

INTRODUCTION

The relatively recent arrival of salmonid pen culture to the east coast of the United States and Canada has presented new economic opportunities for many in the fishing industry. Traditional wild commercial stocks of pelagic and ground fish have shown a serious decline due to overharvest since implementation of the Magnusson Act in the United States and due to a combination of overfishing and adverse environmental conditions in Canadian waters. Fishing communities once dependent on these stocks welcome other means to support themselves. Aquaculture has established itself as one means of supplementing traditional fisheries while at the same time relieving pressure on depleted stocks.

With this new opportunity, however, come new challenges for the resource manager. Pen culture of salmonids has the potential to adversely affect surrounding waters through over-enrichment. Experiences on the west coast of North America (Weston 1986) and northern Europe (Gowan et al. 1988) suggest that pen culture operations can cause environmental problems such as anoxia of bottom waters (Rosenthal et al. 1988), displacement of benthic species (Lim and Gratto 1992; Rosenthal and Rangely 1989; Brown et al. 1987), noxious algae blooms, and release of toxic gases from sediments (Gowan and Bradbury 1987). This paper focuses on benthic impacts.

Environmental regulation of finfish pen culture in Maine and the Atlantic provinces of Canada, until recently, has been guided mostly by experiences from these other regions of the world having very different environmental conditions. Recognizing that the Bay of Fundy and the coast of Maine are dissimilar from these other regions, resource managers have relied on a combination of this "offshore" knowledge and professional judgement. However, the shifting regulatory environment resulting from uncertainty has been to some degree detrimental to both industry and resource management (Maine State Planning Office 1990).

While years of experience in water pollution management have afforded environmental regulators with an ability to predict and quantify impacts associated with various types and quantities of wastes, the simple algebraic equations normally used to predict the concentrations of specific constituents safely allowable in a receiving water for pipe discharges are inappropriate for pen culture permits. Most conventional waste assimilation or allocation models derive from simple dilution equations. Ambient concentrations of a "limiting" constituent are targeted to maintain existing or designated uses within the constraints of the receiving water's quality and flow. Aquatic organisms may be protected from acute or chronic toxicity effects, and human health may be protected from an unacceptable level of risk from exposure to pathogens by establishing an in-stream pollutant concentration target. Effluent concentration limits derived from demonstrated performance of practical technology are then diluted into a statistically derived "worst-case" in-stream low flow. The assimilation capacity developed is straightforward, especially in unidirectional systems such as large rivers with continuously monitored and statistically predictable flows. Once operational, the permitted concentrations and flows may be verified on a case-by-case basis by directly monitoring the discharge as it flows from the pipe.

Discharges from pen culture operations are quite different from discharges most environmental regulators are familiar with. In contrast to conventional land-based "pipe" discharges, waste loads of fish pen aquaculture operations are diffused over the entire operation area, move in three dimensions, and are not easily amenable to direct monitoring. Furthermore, as cause and effect relationships are obscured by unpredictable currents, depositional patterns, storms, and a rapidly evolving aquaculture technology, their impacts are not well understood.

Several predictive models have been developed in the past decade, but they are largely theoretical with little empirical verification. Interim siting guidelines were developed for Puget Sound aquaculture operations by relating potential benthic impact to horizontal current velocity, depth below pens, and annual production (Science Applications International Corp. 1986). In Maine, a predictive model (Maine Dept. of Environmental Protection 1988) adapted from the Puget Sound model was developed to rank potential associated benthic impacts of each operation. Silvert (1992) discussed the strengths and weaknesses of both approaches and proposed a non-linear model based on benthic flux as a more appropriate tool. The Maine model, while limited to ranking potential impact, served its intended purpose of enabling regulators to treating each operator equitably within the industry. Since the model was developed from a set of environmental conditions different from Maine, however, it was not considered capable of predicting actual impact. A new predictive tool reflective of Maine conditions was needed to provide an estimate of environmental risk.

In 1991, implementation of An Act Regarding Aquaculture (State of Maine 1991) provided an opportunity to test and refine Maine's model by requiring standardized environmental and operational monitoring of all net pen culture operations within Maine waters.

METHODS

SITE AND AQUACULTURE OPERATION VARIABLES

Twenty three pen systems were selected for study. Most pen systems were an array of contiguous net pens 6 m deep (Fig. 1); however, in some instances isolated 30 m diameter circles constituted a "system," and the total pen areas ranged from 690 to over 12,000 m^2. Information for each system was compiled for six operational and environmental variables: system age, water depth, mean current speed, areal feeding rate, and tidal range (Table 1). Because many sites were experimental during their first years of existence, age represented the number of years the site had been in "substantial" operation or in the case of small operations, steady state. System ages ranged from 1 to 10 yr with most systems about 4 yr old. Water depth was the average depth of water over which the pens were located measured at MLW. In some instances, bottom slopes were significant resulting in up to a 100% difference between shoal and deeper depths at a site. Depths ranged from as shallow as 6 m to as deep as 25 m. Current was estimated as the average speed near mid-water based on a combination of measurements (deployed current meters, window shade drogues, and professional judgement of divers). Current speeds ranged from 2.5 to 37.5 cm s^{-1}. Tidal range was determined from United States Coast and Geodetic Survey charts. Since most systems studies were in the Cobscook Bay area, tidal range was generally 6 m. Six sites located farther west had tidal ranges between 3 and 5 m. Feeding rate is defined as the weight of feed the operator recorded feeding over the 7-mo peak of the 1992 growing season, April though October, divided by the area of the pen system. Area is defined as the surface area or footprint of the pen array within the lease site. Since both moist and dry feed are used, feed was normalized to 100% dry weight using correction factors of 0.95 dry weight for dry feed and 0.65 dry weight for moist feed. Feeding rates varied considerably, from 15 to 90 kg m^{-2}; this reflects differences in stocking densities, year class, and husbandry.

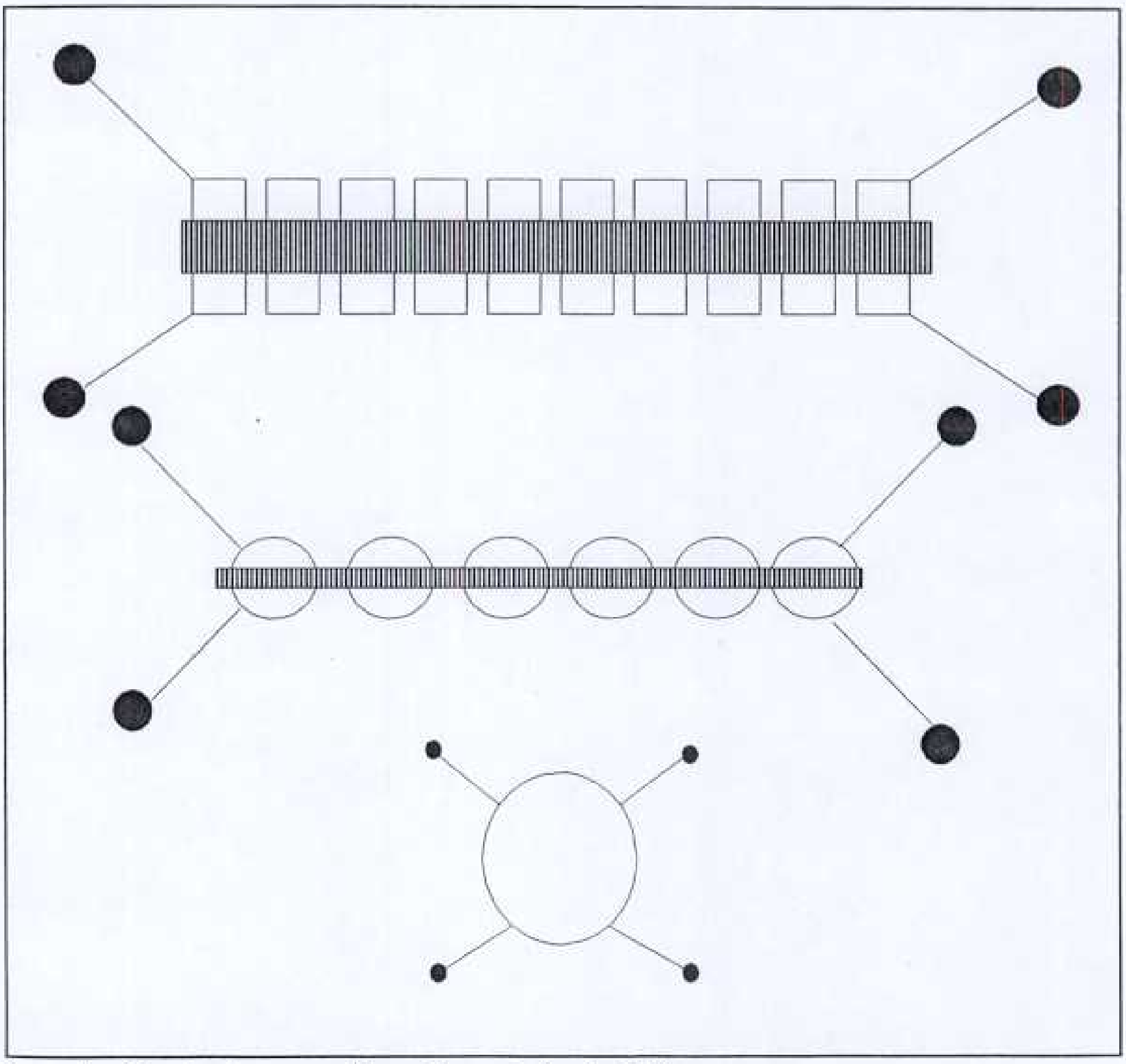

Figure 1. Standard pen configurations at sites in Maine.

Table 1. Operational and environmental variables used to develop benthic index (BI).

System	Year	Area (m^2)	Depth @ MLW (m)	Current ($cm\ s^{-1}$)	Tide (m)	Feed area^{-1} kg m^{-2} $(7\ mo)^{-1}$	Mean score (BI)	Std. error of BI
1	1989	2304	8	8.0	7	38	3.75	0.50
2	1985	2880	9	18.0	7	48	3.25	0.50
3	1989	2880	15	18.0	7	57	2.88	0.25
4	1983	8640	15	12.5	7	29	2.83	0.29
5	1990	9000	15	17.5	7	40	1.83	0.29
6	1989	12130	12	3.0	4	87	2.83	0.76
7	1989	3375	6	37.5	7	60	1.75	0.50
8	1989	7200	11	35.0	7	58	0.75	0.50
9	1988	4602	12	35.0	7	38	0.50	0.58
10	1989	690	12	27.5	7	41	0.38	0.48
11	1990	920	9	17.5	7	15	0.63	0.48
12	1988	3140	8	5.0	4	69	2.13	0.25
13	1987	8190	6	4.5	7	54	2.75	0.50
14	1990	1222	12	30.0	7	27	0.00	0.00
15	1989	8550	11	27.5	7	55	0.63	0.48
16	1988	1728	8	12.5	7	55	1.63	0.48
17	1991	1000	14	30.0	7	34	0.17	0.29
18	1992	1215	12	5.0	4	36	1.67	0.29
19	1988	1620	6	2.5	5	79	2.50	0.50
20	1989	8316	15	2.5	3	40	2.17	0.29
21	1990	3905	25	4.0	3	74	1.00	0.00
22	1992	1347	9	10.0	7	23	0.67	0.58
23	1990	3150	11	15.0	7	30	1.67	0.58

BENTHIC SCORING

Benthic impact was assessed semi-quantitatively by visual observations by four professionals having direct knowledge and experience at each of the sites. Each site was scored on a scale of 0 to 4 where 0 equated to no perceptible difference from natural conditions and 4 to unacceptable benthic impacts. Scores of 1 to 3 reflected increasing levels of benthic enrichment based on type of impact and extent away from pen system. Unacceptable impacts were arbitrarily defined as any one of several conditions: azoic conditions or outgassing adjacent to or directly beneath the pens, *Beggiatoa* sp. mats, feed, and faeces build up extending more than 5 m away from pen footprint (the area of the bottom corresponding to the areal dimensions of the pen system), and hyper dominance of infauna extending more than 5 m away from the pen footprint. Raters scored each site based on a "composite" assessment of impacts they personally observed. The average of the individual scores was used as the benthic score for model development, and standard errors for the scores were also computed.

MODEL DEVELOPMENT

IDENTIFYING THE ROLE OF SITE AGE

Using the data collected in this survey, the Benthic Carbon Loading (BCL) for each site was calculated from the model described in Chapter 1 (Silvert 1994), and the calculated BCLs were compared with the Benthic Scores described in the previous section. The results of this comparison are shown in Figure 2; and although there is clear correlation, it is weak and the Benthic Carbon Loading (BCL) by itself is not a good predictor of the Benthic Score.

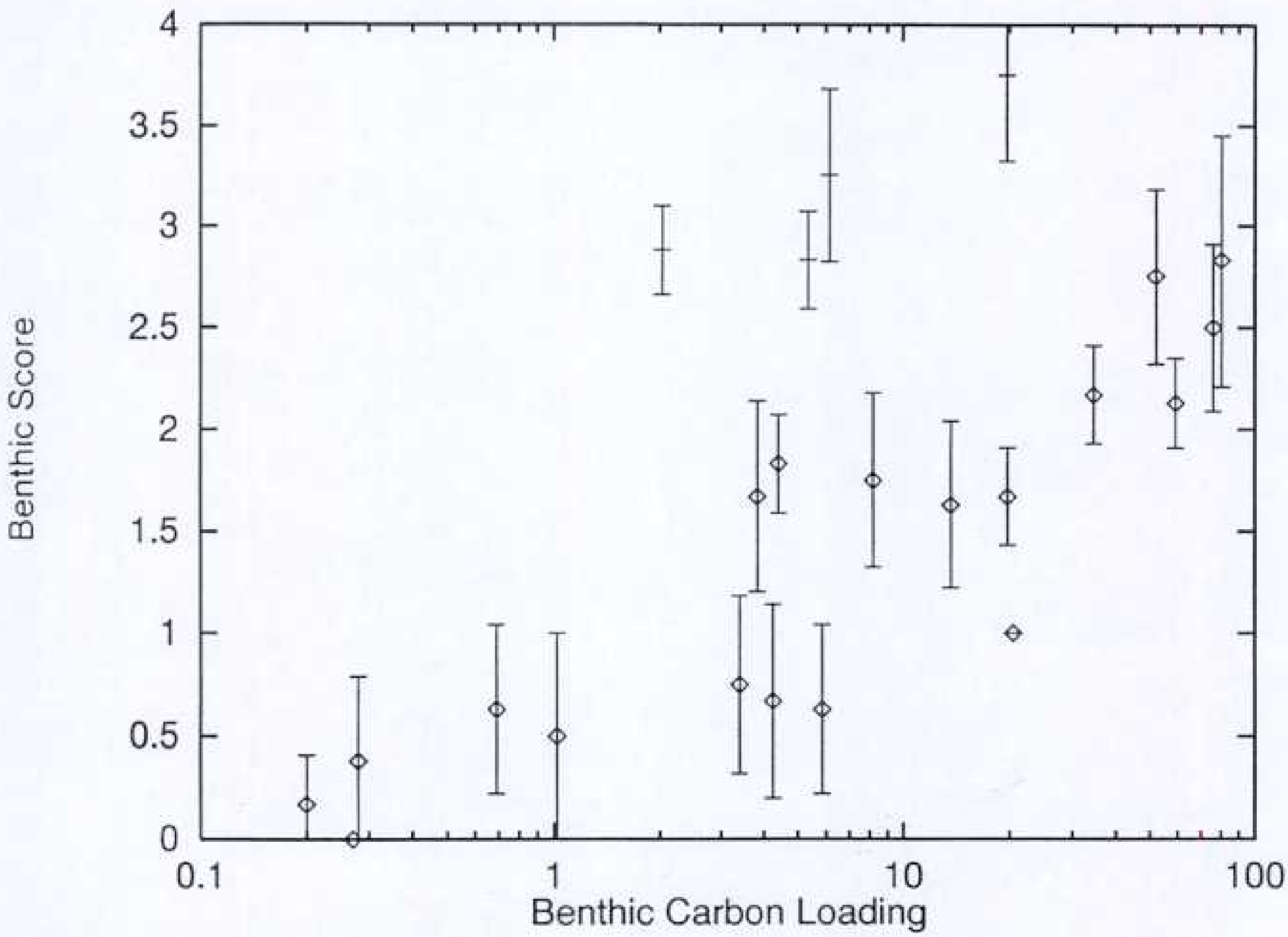

Figure 2. Benthic Scores plotted against Benthic Carbon Loading (BCL) (g C m^{-2} d^{-1}) as described by Silvert (1994) in Chapter 1 of this report. The sites represented by horizontal lines rather than circles are significantly older than the others or are in locations that have a long history of organic loading from other sources.

The inclusion of additional information about the sites greatly reduced the scatter about the regression line. Some of this information, such as that relating to husbandry practices, is confidential and cannot be released for publication. Other factors, such as the geometry of the site and proximity to headlands and other features which might affect the transport and settling of particulates, involve very site-specific considerations. Very few of the sites actually conform to any of the simple configurations shown in Figure 1; and although it is possible to modify the calculation of BCL to allow for different cage geometries, this type of detailed physical transport calculation is very labour-intensive and seemed inappropriate at the present stage of model development (see Gowen et al. 1994, Chapter 2 of this report, for details of this sort of calculation).

We noticed that points corresponding to older sites generally lay above the regression line, while points from more recently occupied sites were below it, which seems reasonable on biological grounds. We would expect that it would be the cumulative effect of several years of organic carbon loading that would have the greatest impact, and consequently that older sites would have higher scores for benthic degradation. Furthermore, among these older sites (represented by horizontal lines in Fig. 2) the Benthic Scores increased with BCL in the same way as with the newer sites, which suggests that there might be a limiting value to the score which depends on the loading. Based on these observations we proceeded to try to develop models which were both biologically reasonable and which agreed with the data.

MODEL FORMULATION

One type of common model which suggests itself in this situation is an uptake-clearance model of the form:

$$d(AC)/dt = (BCL) - k \times (AC) \tag{1}$$

where AC is the Accumulated Carbon under the cage. The first term, (BCL), represents the input flux of organic carbon to the bottom, while the second term, $k \times (AC)$, represents loss by resuspension, microbial degradation, and consumption by fish and invertebrates (k can be interpreted as a combined resuspension + biological consumption rate). Although there are clearly many deficiencies in this model, particularly in the second term (these are discussed below), it seems to provide a reasonable starting point for the analysis.

By setting the derivative d(AC)/dt equal to zero we can calculate a limiting level of carbon accumulation, $AC_{lim} = (BCL)/k$, which is the level at which removal processes take away carbon at the same rate at which it is deposited (i.e., BCL). The Accumulated Carbon under a farm site at any time is:

$$AC = AC_{lim} \times [1 - exp(-kt)] \tag{2}$$

where t is the age of the site and k is a constant. This function starts off at a value of zero when $t=0$ and increases asymptotically towards AC_{lim} as the age of the site increases.

Although it is reasonable to believe that AC (Accumulated Carbon) should be a better predictor of benthic impacts than BCL by itself, since it accounts for the length of time the bottom is impacted, a similar argument can be raised against it. We would not expect BCL to be a complete predictive variable, since it takes time for organic carbon to build up on the bottom and for adverse effects to occur. Similarly, the presence of a layer of organic matter on the bottom might not lead to instantaneous adverse consequences; it may take time for biological and chemical reactions to occur which lead to oxygen depletion, gas generation, and other deleterious effects. Consequently we have investigated the possibility that benthic impact is actually a second-order effect, driven by the existence of a layer of accumulated carbon in much the same way that organic carbon itself builds up as a result of loading.

If we represent the deterioration of the bottom by an uptake-clearance equation similar to Equation 1 we get:

$$d(BD)/dt = d \times (AC) - r \times (BD) \tag{3}$$

where BD is the degree of Benthic Deterioration and d is a degradation rate and r a recovery rate. This equation is based on the argument that the more accumulated carbon is present under the cages, the more rapidly the bottom deteriorates, and that this deterioration is balanced by some sort of recovery process.

The relationship between Accumulated Carbon (AC) and Benthic Deterioration (BD) over time is shown in Figure 3. It can be seen that AC begins to build up very rapidly as soon as the site begins operations, but that BD takes a while to begin to develop, since it is driven by AC and not directly by the Benthic Carbon Loading (BCL) itself; this is why we refer to benthic impacts as a second-order process.

In order to relate BD to the observed Benthic Scores described above, we have to deal with the constraint that the Benthic Scores are evaluated on a scale of 0 to 4, while the level of Benthic Degradation calculated from Equation 3 is unlimited. We have therefore arbitrarily mapped BD to a scale of 0 to 4 by using the transformation:

$$BI = 4 \times \sqrt{BD} / (1 + \sqrt{BD}) \tag{4}$$

to generate a Benthic Index (BI) lying between 0 and 4. Figure 4 shows the relationship between the observed Benthic Scores and the Benthic Index values predicted by this analysis. Comparison with the dashed line which corresponds to perfect agreement shows that this Benthic Index is a reasonable predictor of Benthic Scores as a measure of bottom conditions.

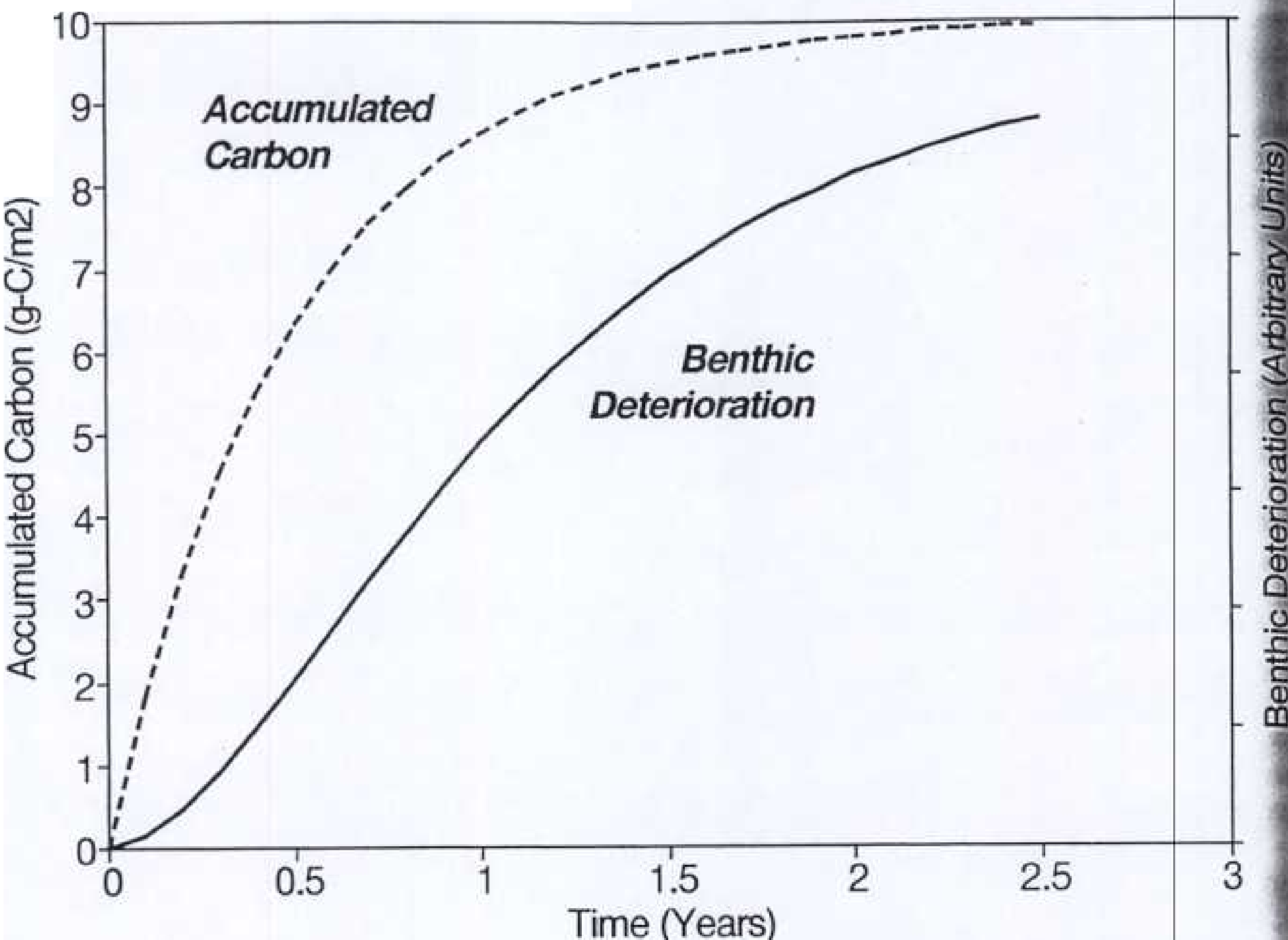

Figure 3. Comparison between dynamics of Accumulated Carbon (AC) and Benthic Deterioration (BD) based on the first and second order uptake-clearance models described in the text (Equations 1 and 3).

ANALYSIS AND INTERPRETATION OF THE MODEL

The results shown in Figure 4 indicate that a Benthic Index based on the second-order model of Benthic Deterioration is a reasonable predictor of benthic impacts, and that it might be worth refining the system of simple uptake-clearance models described in Equations 1 and 3. The greatest weakness in Equation 1, the first part of this model, is the set of assumptions that go into the clearance term, (AC)/k. We would not expect the rate of organic carbon removal to be strictly proportional to the amount present, since at low fluxes the natural grazers could probably remove any organic carbon that settles, while at high fluxes the amount sedimenting is likely to overwhelm natural removal mechanisms. The age of the carbon is also a factor, since the model does not distinguish between fresh food pellets and faecal matter on one hand, and aged buried

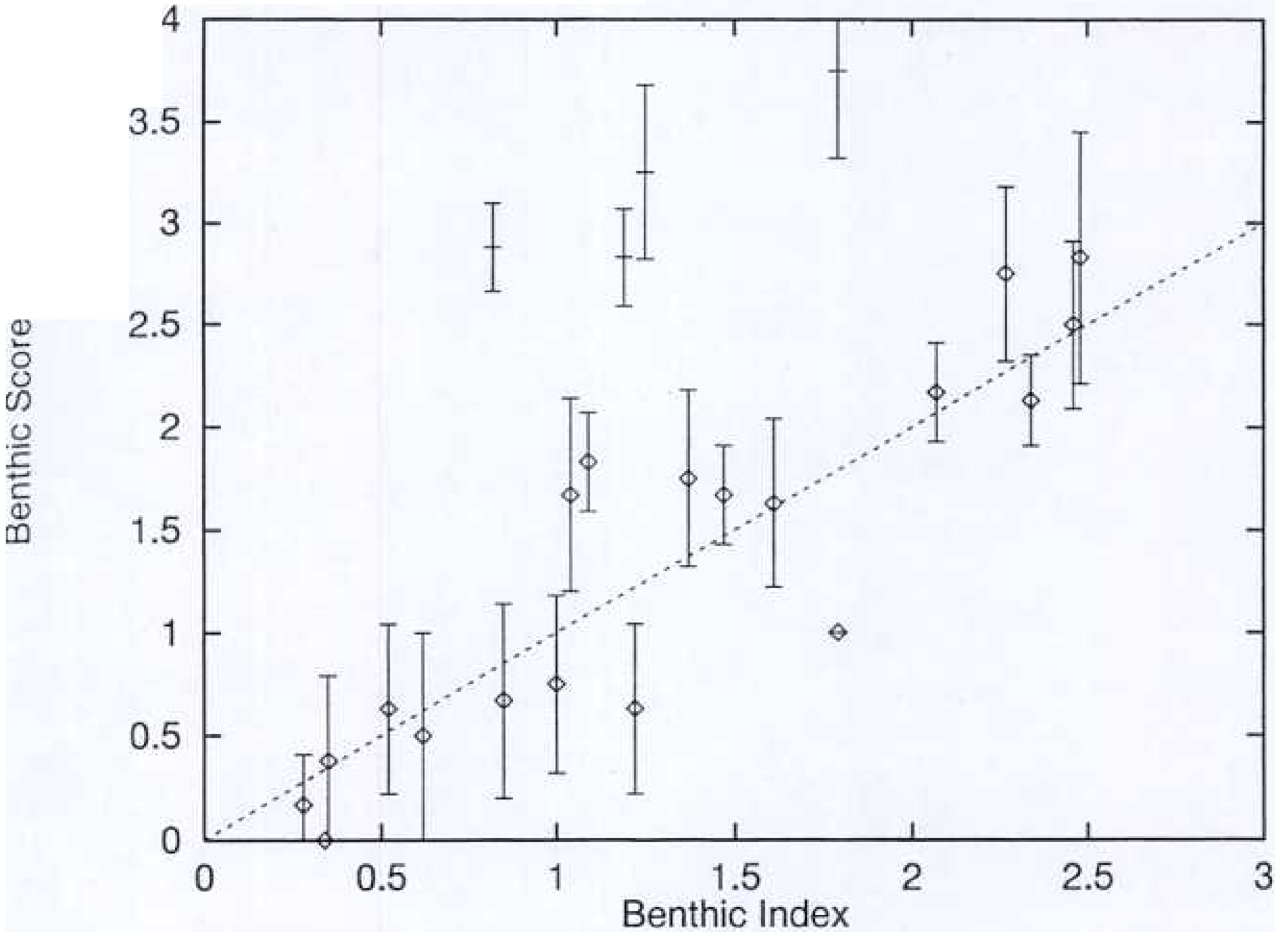

Figure 4. Benthic Scores plotted against predicted scores based on the uptake-clearance model. The four sites shown by horizontal lines above the other points represented by circles are considerably older or have different management histories than the others. The dashed line represents equality between predicted and observed scores.

organic carbon and *Beggiatoa* mats on the other. As for Equation 3 describing Benthic Deterioration, this is very speculative and we do not as yet have a direct measurement of any quantity which could be interpreted as a proxy for BD. However, the pattern of deterioration represented by the solid line in Figure 3 appears reasonable and appears to relate well to other, mostly anecdotal, information on bottom changes under fish cages. Certainly the basic shape of this curve, which suggests that it takes some time before serious benthic impacts are observed, seem reasonable to fish farmers and scientists with experience in this area.

Another weakness of the model, although one that might be more easily dealt with in the framework of this analysis, is that it assumes that the Benthic Carbon Loading is proportional to the amount of feed consumed. This ignores differences in feeding efficiency between farms, but it is known that significant differences exist. Information about these differences is often available to regulatory agencies, but it generally involves proprietary data and must be used with discretion.

DISCUSSION

The four "outliers" shown in Figures 2 and 4 might be explained by one or more of several factors unique to these sites. They are more heavily developed in terms of age and percent pen saturation of the lease area. The three most distant outliers are located within the same cove which has a history of organic loading from a fish processing plant. All four outliers are under the same ownership and management, suggesting that perhaps husbandry is a factor. And all four are unique in that they are sited within 25 m from other systems of similar size, and it is possible that the resultant density of pen structures reduces the actual currents in the vicinity of the cages. We tested this hypothesis by recalculating the predicted score using a current velocity of zero, which indeed moves the outliers to the right and reduces the disagreement between theory and experiment, as shown in Figure 5. However, the removal of current dispersion effects does not completely resolve the discrepancies, so it appears that other factors must be involved.

Although the limited data used in this study do not permit us to identify a definitive relationship between carbon loading and benthic impact, our model provides a good qualitative prediction that could be used as a tool for industry, regulators, and scientists alike. At present, it is the only means by which benthic degradation can be forecast for a specific pen culture operation. The forecast can be used in several ways. For new operations, environmental managers may use the model to design a baseline monitoring plan. A site/operation combination ranking high on the index may warrant a more intensive pre-start-up characterization than one ranking lower on the index. For existing operations ranking high, both spatial distribution and frequency of sampling might be increased at least until analysis of monitoring data supports a revision to the original monitoring plan. Given the scarce resources available to properly administer environmental and natural resource programs, the model enables managers to efficiently allocate their time and budget where it is likely to be the most effective. Rather than scrutinizing all operations at the same level of effort, those with the highest probability of causing an unacceptable impact would be monitored most closely.

From an industry perspective the model has perhaps even greater value. Knowing the regulatory environment in which permitting decisions are made can help avoid permitting delays by allowing an applicant to understand the decision-making process. The model may also benefit operators already in production in that the difference between the "expected" benthic score derived from the model and the actual benthic score observed through monitoring may reflect to some degree the efficiency of

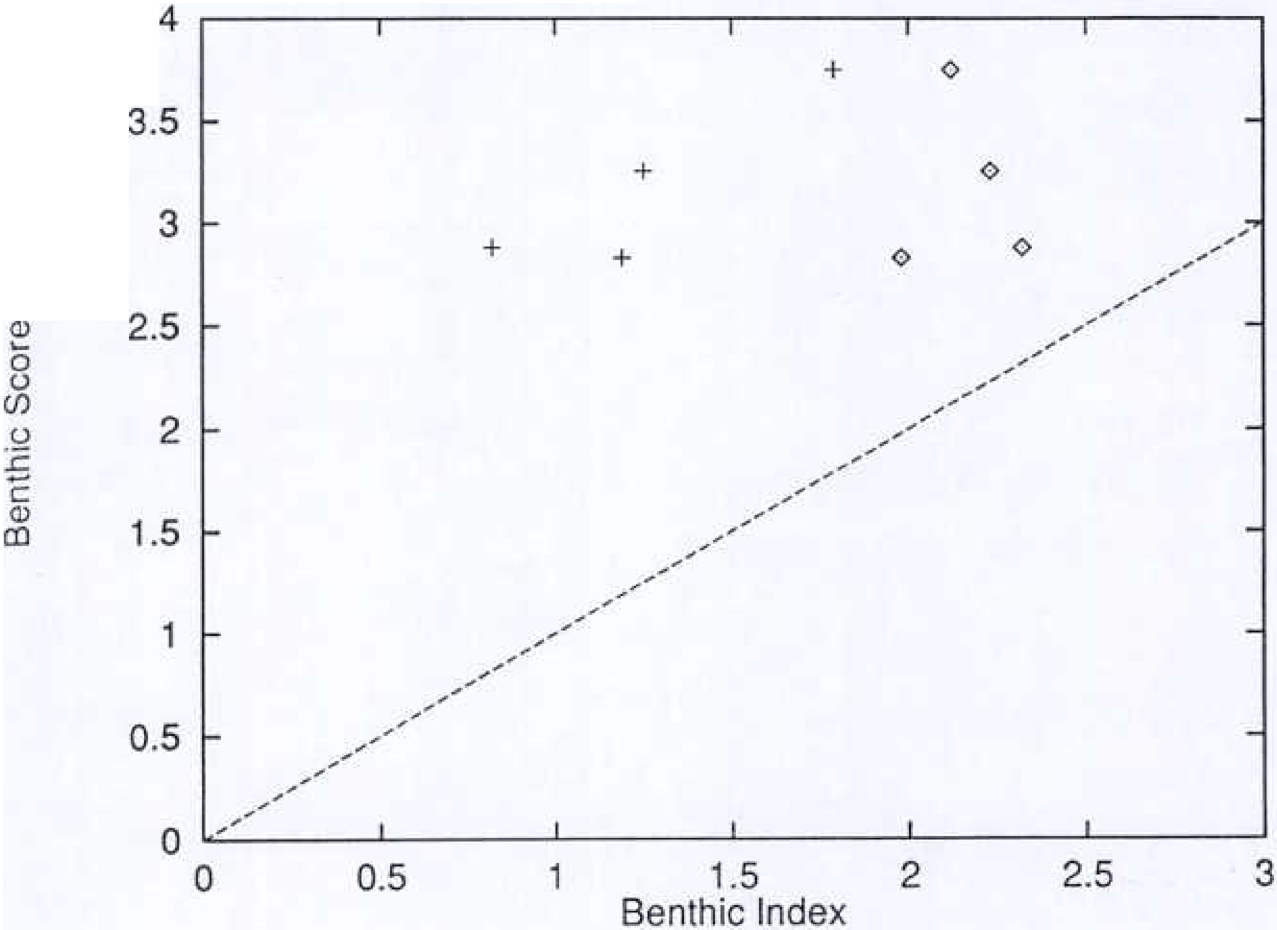

Figure 5. Effect of suppressing the dissipation of settling particles for the first four sites listed in Table 1. The crosses show the original positions of the points representing these sites, while the diamonds show the results obtained by setting the current speed equal to zero so that the depositional area is equal to the area covered by the pens. The Benthic Scores (Y-axis) are the same, but the predicted Benthic Index (X-axis) increases, which improves the agreement between Benthic Index and Benthic Score but does not fully resolve the discrepancies.

husbandry. Operations having higher observed impacts than predicted by the model might consider whether husbandry practices related to feed conversion is responsible. Clearly, converting more feed into fish flesh rather than enriching the benthic environment is desirable for all.

From a scientific perspective the model represents a step in the development of models describing the evolution of benthic impacts under continued exposure to benthic carbon loading. Already, in attempting to interpret and explain the outliers, several issues have arisen and provided quantitative information about the influence of husbandry on benthic impacts, the importance of pen configuration on organic deposition and clearance rates, and the effect of pre-existing and off-site near-field organic discharges.

This model is an important first step toward understanding the relationship between finfish pen culture operations, local environmental conditions, and benthic "quality." In the process of the model's development, inadequacies were revealed in sampling and data reporting protocols which offered valuable feedback on the monitoring program. The model appears to provide a reasonable prediction of benthic impacts associated with pen culture and is a substantial improvement over the formula used prior to its development. However, it is not a replacement for field verification and should be used with discretion. The model should be seen as a first step, one which we feel has been successful; and it shows promise for further refinement and offers a good basis for future research.

CONCLUSIONS AND RECOMMENDATIONS

Open-water net-pen aquaculture offers opportunities for fishermen attempting to harvest declining wild fish stocks. However, environmental managers and especially regulators have pointed out that environmental impacts must be minimized if productivity in the new industry is to be sustainable. Regulation has been largely arbitrary and inappropriately treated in the same manner as conventional industrial discharges. Consequently, the regulatory environment has been unpredictable. In 1991, the Maine legislature enacted an aquaculture law requiring development and implementation of a standardized monitoring program.

First-year monitoring results from 23 operations in downeast Maine have enabled us to develop an initial model which predicts the amount of benthic organic enrichment. Unlike site specific studies detailing local processes, this model is more robust and especially applicable to regulators who deal with coast-wide regulation and monitoring of an entire industry. The model may also be used by industry management to assess husbandry performance and scientists to formulate and test hypotheses.

Inherent in the development of any model lies the possibility of inappropriate application. We caution regulators and policy makers to use the model in conjunction with field verification monitoring before any decisions are made.

This initial work shows the potential for fruitful research into the development of a more refined benthic impact model through a more standardized data collection. We recommend that aquaculture monitoring programs focused on these environmental and operational conditions in collaboration with research programs be used to build the next generation models.

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