



## ASSESSMENT OF FINFISH CAGE AQUACULTURE IN THE MARINE ENVIRONMENT



Figure 1: Map of the Department of Fisheries and Oceans' (DFO) six administrative regions.

### Context

*Finfish cage aquaculture involves holding large numbers of fish in a restricted space. The cages are sites for the introduction of feed, other nutrients and metabolic wastes, and oxygen is removed from the water column directly due to respiration by the fish and indirectly due to breakdown of the feed and metabolic wastes by marine micro-organisms. These changes can occur both in the immediate vicinity of cages (near-field) and at some distances away (far-field). Concern has been raised about the possible effects of these processes on coastal marine ecosystems.*

*Both the siting of finfish cage aquaculture facilities and their maximum capacity are currently regulated in part to protect the health of marine ecosystems. However the regulatory frameworks have been largely site-specific, developed locally or regionally, and have not been reconciled with each other around the country. More importantly, the scientific foundations for the approaches to regulation have rarely been linked explicitly to provisions in the management approaches.*

*A meeting was held in Sidney, BC, in February 2005, to review a number of scientific working papers, which brought together published information and original research on the evidence for effects of finfish cage aquaculture on components of marine ecosystems. The information in the working papers was augmented by the knowledge of meeting participants with backgrounds in science, management, the aquaculture industry, and public interest groups. The meeting participants identified a large number of knowledge gaps which require further research, and these are reported in the Proceedings of this meeting (2005/006). However, with the knowledge currently available, a number of conclusions were drawn about the evidence for environmental effects of finfish cage aquaculture and the management practices of aquaculture to ensure a viable industry in a healthy marine ecosystem.*

## SUMMARY

- The scientific foundations for management of the ecosystem effects of aquaculture are currently incomplete. However the tools and approaches used by DFO's Habitat Management for site-specific management are consistent with the scientific information that is available.
- While uniform industry-wide operational thresholds are inappropriate because of substantial variation in background levels in the indicators of effects on many space and time scales, consistent regulatory *approaches* with regional or local quantitative thresholds are possible.
- The management tools and approaches currently in use are focused primarily on near-field and site-specific regulatory applications. There may be far-field and cumulative effects, and quantifying and managing them will require new or modified approaches.
- Benthic monitoring methods suitable for assessing environmental effects of marine finfish aquaculture include the following: conventional macrofaunal community analysis, total free sulphides and zinc/copper (Zn/Cu) in surface sediments, underwater (U/W) video- and photography, and dissolved oxygen. All of the suggested benthic methods have strengths and weaknesses. All are useful for near-field monitoring but may be less suitable for far-field monitoring.
- The aquaculture waste model DEPOMOD has been applied at numerous fish farm sites around the world. Tests of the model in British Columbia (BC) were generally encouraging, and several practical pathways for further development of the model were identified. It is particularly important that uncertainty regarding model parameters be reduced through further research. DEPOMOD should not be used in isolation, and model predictions do not replace real observations and monitoring data.
- Dissolved oxygen is not yet an easily applied regulatory tool on a specific case-by-case basis, and views were mixed regarding its promise as a candidate for monitoring environmental quality in the coastal zone. However, it is one of the few options available for monitoring over hard bottoms. It is also a useful tool for predicting and assessing far-field effects in environments where oxygen levels may be a concern.
- Under some circumstances, finfish aquaculture has the potential to alter the trophic status of inlets on far-field scales. Different coastal regions may be more or less nutrient limited, and ecological responses to nutrient enrichment from fish farms will therefore not be the same in all areas. Variations in farm density and the distribution of farms and other sources will also influence the probability of far-field eutrophication effects from all sources.
- Mass balance calculations can be used to estimate the fractionation of aquaculture wastes and to compare the input of nutrients from finfish culture with other supply pathways. The reliability of such estimates will depend on the quality of the model parameters and the accuracy of the description of farm operations and ecosystem processes.
- The sensitivity of a particular marine habitat can be assessed by the following:
  - listing physical, chemical and biological factors which may affect the habitat;
  - quantifying these effects in terms of endpoints (e.g., loss of a portion of the habitat, reduction in the functional integrity of the habitat). Of the habitats examined, eelgrass is more sensitive to effects of aquaculture than kelp.

## DESCRIPTION OF THE ISSUE

Both the siting of finfish cage aquaculture facilities and their maximum capacity are currently regulated in part to protect the health of marine ecosystems. However the regulatory frameworks have been developed locally or regionally, and have not been reconciled with each other around the country. More importantly, the scientific foundations for the approaches to regulation have rarely been linked explicitly to provisions in the management approaches. This Science Report applies the information from a number of working papers (see list of CSAS Research Documents under the Sources of Information section) and dialogue among experts to partially consolidate the scientific information referred to above, and relates this to existing management approaches.

## ASSESSMENT OF ISSUE, CONCLUSIONS AND ADVICE

In the discussion of the individual working papers, a number of common themes emerged. These were brought together in a set of overall conclusions.

### Benthic Monitoring Methods

#### Assessment

Finfish cage aquaculture potentially may affect the benthic community and composition of sediments around culture facilities, via several pathways. These effects are known to vary with many other factors about both the specific ecosystem and the practices of culture facilities. There is substantial debate about what to monitor in the marine benthic environment around culture facilities and how to use the information from benthic monitoring in regulating the facilities. From a literature review, presentation of results of new research and discussion, the following conclusions were drawn about methods for monitoring biological and chemical properties of the benthos and surface sediments in the area around cage aquaculture facilities.

#### Conclusions and Advice

1. The following methods presented in the working paper are suitable for assessing environmental effects of marine finfish aquaculture: conventional macrofaunal community analysis, total free sulphides and zinc/copper (Zn/Cu) analyses in surface sediments, underwater (U/W) video- and photography, and dissolved oxygen analyses. The applicability and practicality of each method is dependent on the environment being monitored, the strengths and weaknesses of the method, and the severity of the effects being assessed.
2. The choice of monitoring methods to be used at a particular location is determined by the existing bottom substrate type and spatial heterogeneity (see Fig. 2).
3. The strengths and weaknesses of each benthic monitoring method are summarized in Table 1. Threshold levels are available for conventional macrofaunal community analysis, total free sulphides and dissolved oxygen (as described in the working paper and Tables 1 and 2). The threshold levels of macrofauna and total sulphide, applicable only in fine-grained sediments, are linked to the organic enrichment gradient of Pearson and

Rosenberg (1978) and consequently may be more useful for Habitat Management purposes than other available methods.

4. A step-wise approach is recommended to identify sites where more detailed information may be required. More specific methods may be applied if initial cost-effective, relatively rapid methods indicate the potential for thresholds to be exceeded. The decision tree in Figure 2 can be used as a steering tool for additional methods.
5. Relative to sediment geochemical methods, macrofaunal community analysis is comparatively costly and time consuming. However, the latter method provides information about benthic biological responses integrated over time and space. No comparative information is available for the other methods listed in Table 1.
6. Full taxonomic (species-specific) analysis may not be required in site comparisons (farm/reference), since the macrofaunal community analysis can often be carried out by identifying to higher taxon (genus, family, class) only. However, this short-cut approach is not applicable where the organic enrichment gradient threshold is yet to be established.
7. Videography and photography are useful for all substrate types (soft, mixed, hard) but may only qualitatively (semi-quantitatively) assess changes in epifauna and sulphur bacterial mat coverage (i.e., visual assessment).
8. Measures of Zn/Cu, even when normalized for grain size effects and mineralogy (using lithium (Li) correlations), cannot be directly related to sediment toxicity because the measures do not consider the bioavailability of metals.
9. Zn with and without Li normalization can be a useful tracer of the spatial range at which effects may extend (although the ecological significance of the effect is not determined by this method). Interpretation of the distribution is dependent on the amount and nature of Zn added to feed by the manufacturer and sediment redox conditions.
10. Sampling design is recognized as critical in applying all benthic methods, but this was not part of the review of methods presented in the working paper. Despite this, there was consensus that application of any benthic monitoring method should take into account seasonal effects.
11. Reference sites should be sampled – as an initial sample in a time series analysis and at the end of an organic enrichment gradient in a spatial study. Reference sites should be carefully chosen as part of the pre-survey.
12. All of the suggested benthic methods are more useful for near-field monitoring but may not be as useful for far-field monitoring due to the different spatial resolution. These methods are likely to be among the tools used in the far-field, but the level of resolution will differ. Dissolved oxygen (and suspended particulate matter) can be measured over hard substrates when bottom sediments cannot be collected.
13. Methods considered to be important for further research include acoustic methods, U/W photography, video and sediment profile imaging, geochemical methods, use of bioindicator tools (such as taxonomic distinctness), and methods to monitor crevice macrofauna.

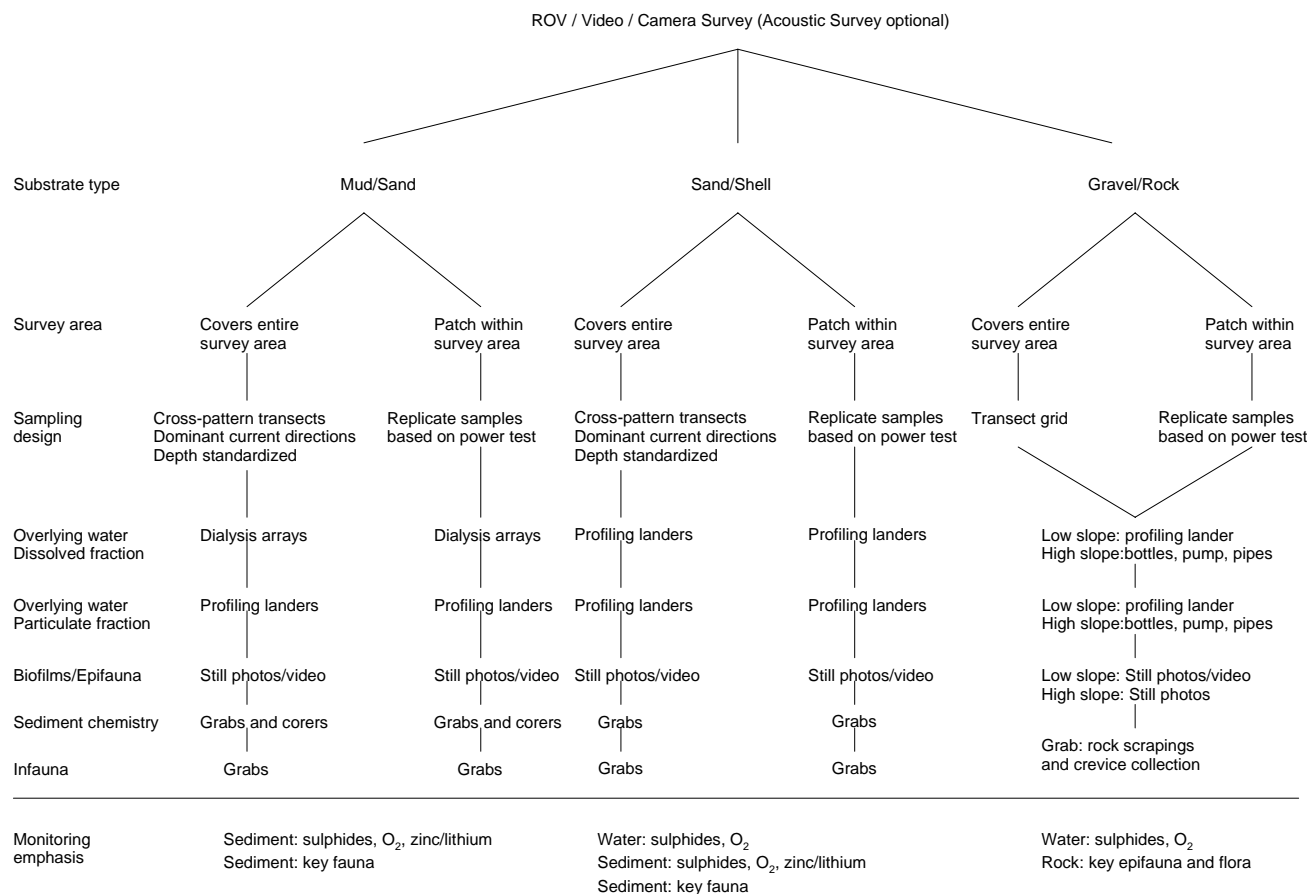


Figure 2: Decision tree to assist in choices of recommended benthic sampling methods (Sutherland, 2004).

Table 1: Strengths/Weaknesses of organic enrichment monitoring methods based on sediment sampling and grouped according to applicable goals (numbers refer to Table 1A).

Strong = \*\*\*, Weak = \*, 0 = not applicable, ? = unknown

OPERATIONAL CRITERIA	ENVIRONMENTAL MONITORING METHOD									
	Conventional Macrofauna		Total S <sup>-</sup>		Zinc/Copper		U/W Photo/Video		Dissolved Oxygen	
Goals	1-3	4	1-3	4	1-3	4	1-3	4	1-3	4
Soft substrate	***	*	***	*	**	*	**	*	***	*
Mixed substrate	0	0	0	0	0	0	**	*	***	*
Hard substrate	0	0	0	0	0	0	**	*	***	*
Scientific defensibility	***	*	***	*	**	*	**	*	***	*
Statistical testability	***	*	***	*	**	*	**	*	***	*
Threshold availability	***	*	***	0	?	?	?	?	**	*
Cost-effectiveness	*	0	***	0	?	?	?	?	?	?

Table 1A: Monitoring goals used in detecting and measuring organic enrichment effects resulting from finfish aquaculture.

GOALS	EFFECT MEASURED	HYPOTHESIS
1. Practical	Determines a relative degree of change	None, it triggers remediation or other management activity if a specified threshold (reference point) for a variable is exceeded
2. Site comparison	Difference between treatment/reference sites	H <sub>0</sub> reference = treatment site H <sub>1</sub> reference ≠ treatment site
3. Temporal	Before/after status	H <sub>0</sub> reference = treatment at t <sub>0</sub> H <sub>1</sub> reference ≠ treatment at t <sub>1</sub>
4. Geographical	Limits of effect	H <sub>0</sub> reference condition throughout the study area H <sub>1</sub> reference and affected area delimited within the study area

Table 2: The organic enrichment gradient (after various authors). The organic carbon sedimentation rate increases from left to right. From DFO 2004.

TYPE OF MEASURE	SUCCESSIONAL STAGES				REFERENCE
	III	II	I	0	
Microbial	Normal	Oxic	Hypoxic	Anoxic	Poole et al. (1978)
Macrofaunal	Normal	Transitory	Polluted	Grossly polluted	Pearson and Rosenberg (1978)
Geochemical S <sup>2-</sup> , μM	Normal <300	Oxic 300-1300	Hypoxic 1300-6000	Anoxic >6000	Wildish et al. (2001)

## DEPOMOD

### Assessment

DEPOMOD is a computer model developed in Scotland, but now used in many jurisdictions, including parts of Canada, to predict patterns of aquaculture waste sedimentation around finfish aquaculture sites. Some information is provided by the model about potential ecological effects through changes in benthic community composition. An overview of the model and results of testing its application in BC were presented to the meeting. The information in the working paper, presentation and discussion among experts, led to the following conclusions.

### Conclusions and Advice

1. The aquaculture waste model DEPOMOD has been applied at numerous fish farm sites around the world and has been shown to be a good general predictor of carbon flux and some measures of sediment geochemistry and benthic community response.
2. The model was tested at a reasonably energetic farm site in BC. Model predictions of relative carbon flux correlated very well with field observations of sediment chemistry and benthic community structure, suggesting that it is a promising tool.

3. Absolute values defining carbon flux could not be made at this time because of uncertainty in some model parameters and inadequacy of technologies for measuring carbon flux. There was no consensus on the values that should be used for these parameters, generally because of information gaps and lack of defensible data.
4. The uncertain model parameters include the following:
  - carbon concentration of feed particles (values tested 44, 55 and 65%);
  - carbon concentration of faecal material (values tested 30, 40 and 50%);
  - proportion of feed wasted (values tested 0, 5, 10%; discussions suggested values may range between 2 and 15%).

Research is ongoing to address the above noted uncertainties.

5. There was agreement that the resuspension module should not be applied, until we better understand the conditions under which it is appropriate for assessing benthic effects under the conditions of the BC site examined. This understanding will require research on critical resuspension thresholds of aquaculture wastes and the relative importance of resuspension processes on the nature and scale of effects of predicted carbon flux on benthic geochemistry and community composition.
6. The model is currently being used as a decision-support tool in BC. It should not be used in isolation, and model predictions do not replace real observations and monitoring data. Model outputs can nonetheless be used in field sampling design and farm configuration decisions. DEPOMOD is a useful planning tool.
7. For improved confidence in model application, it is essential that model outputs for deposition be validated against measured flux rates in the field. Furthermore, the model must be tested at additional sites that reflect the different environmental conditions encountered in Canada.

## **Dissolved Oxygen**

### **Assessment**

Dissolved oxygen (DO) in the water column is used directly by the cultured fish for respiration, and indirectly through decomposition of waste products which may accumulate around the facility. There has been substantial debate about the conditions under which the increased DO demand could produce consequences in the marine ecosystem, and if those conditions occur where culture facilities are located. From a literature review, presentation of results of new research and discussion, the following conclusions were drawn about the potential for DO to be a useful indicator for assessing effects of finfish cage aquaculture (near- and far-field) around the facilities.

### **Conclusions and Advice**

1. Dissolved oxygen is not yet an easily applied regulatory tool on a specific case-by-case basis, but is a promising candidate for monitoring environmental quality in the coastal zone.
2. Effects of aquaculture on DO are not as readily quantifiable as those of other activities with point sources.

3. Quantifying background or natural DO levels and monitoring locations will require consideration of location-specific DO conditions on a range of spatial and temporal scales appropriate to the particular coastal zone. Fjord and upwelling systems, such as those found in BC and Newfoundland, exhibit great variability in DO concentrations.
4. Because of the substantial effort and resources required to monitor DO concentrations and determine background levels, cost-effective methods and technologies should be used. The monitoring sites should be representative of the area or positioned at locations of known or anticipated low DO conditions.
5. Experience to date shows that some jurisdictions have not had success applying DO as a regulatory tool in the mixing zone (near-field). Views are mixed on whether it has promise for this application. However, it is one of the few options available for monitoring over hard bottoms. It is also a useful tool for predicting and assessing far-field effects in environments where oxygen levels may be a concern (e.g., fjords, upwelling systems).
6. While DO has been used in planning and management and regulatory models, work is needed to develop and test mass balance models.

## **Eutrophication**

### Assessment

Eutrophication is defined here as an increase in the energy flow in and nutrient cycling by an ecosystem. The nature of eutrophication and both its causes and consequences in specific areas has been debated with regard to the regulation of many marine industries which affect coastal and estuarine ecosystems. Recently the debate has extended to include the possibility that under some conditions intensive finfish cage aquaculture may contribute to eutrophication in areas from hundreds of meters to as much as a few kilometres from the concentrations of culture facilities. From a literature review, presentation of results of new research and discussion, the following conclusions were drawn about the potential for eutrophication to be a consequence of finfish cage aquaculture.

### Conclusions and Advice

1. The term 'eutrophication' can be used to describe a process (changes in rates of nutrient or organic matter supply) or a state (level of nutrients or organic matter in an ecosystem). Trophic status is a function of the cumulative inputs of nutrients and organic matter from all sources and the processing of these materials by the ecosystem.
2. Elemental budgets and mass balance calculations can be used to estimate the relative magnitude of multiple processes that supply and remove nutrients or organic matter in coastal ecosystems. To estimate absolute magnitude of these processes, it is necessary to quantify all source and sink terms precisely.
3. Estimates of cycling rates or concentrations of dissolved nutrients and organic matter provide useful broad-scale indicators of trophic status in marine coastal ecosystems.
4. Under some circumstances, finfish aquaculture has the potential to alter the trophic status of inlets on far-field scales. Different coastal regions may be more or less nutrient limited, and ecological responses to nutrient enrichment will therefore not be the same in



all areas. Variations in farm density and the distribution of farms and other sources will also influence the probability of far-field eutrophication effects from all sources.

5. Mass balance calculations can be used to estimate the fractionation of aquaculture wastes and to compare the processing of nutrients by finfish with other environmental pathways. The reliability of such estimates will depend on the quality of the model parameters and the accuracy of the description of farm operations, other nutrient sources and ecosystem processes.
6. Such scoping calculations provide information about the potential for inlet-wide nutrient and organic matter enrichment on which decisions about the potential for far-field effects may be based and should be tested as first-pass assessment tools of the effects of large farms and the cumulative effects of multiple farms.
7. Due to multiple natural and anthropogenic sources, it will be difficult to establish direct links between amounts of dissolved nutrients and organic matter, and site-specific inputs from aquaculture.
8. Seasonal variations can be represented using these calculations, making it possible to focus on the time of year when biological consequences are greatest.
9. Sites where fine particles accumulate may be regions where ecological effects from nutrient and organic matter enrichment from all sources can be observed. Intertidal zones (and their algal communities) and deep water sinks may be such sites.
10. Future work should compare and harmonize empirical data with mass balance estimates.

## **Habitat Sensitivity – Eelgrass and Kelp**

### **Assessment**

Coastal intertidal and subtidal vegetation play an important role in marine ecosystems, as habitats and sometimes food for many fish and invertebrates, particularly younger life history stages, and in some cases seabirds. Hence effects of finfish cage aquaculture on these marine plants could have widespread secondary effects on marine ecosystems. Previous work had identified eelgrass and kelp as being of particular interest in this context. From a literature review, presentation of results of new research and discussion, the following conclusions were drawn about the sensitivity of the two species of macro-algae to effects of marine finfish aquaculture. The discussion also included some consideration of the sensitivity of other habitat-forming species to aquaculture.

### **Conclusions and Advice**

1. It is possible to define the term 'marine habitat sensitivity' and apply it for management purposes. Habitat sensitivity can be defined in relation to the degree and duration of damage caused by a specified external factor. Sensitivity may refer to structural fragility of the entire habitat in relation to a physical impact, or to intolerance of individual species comprising the habitat to environmental factors, such as exposure, salinity fluctuations or temperature variation (ICES 2002).
2. The sensitivity of a particular marine habitat can be assessed by the following:

- listing physical, chemical and biological factors which may affect the habitat;
  - quantifying these effects in terms of endpoints (e.g., loss of a portion of the habitat, reduction in the functional integrity of the habitat).
3. It is important to describe any potential interactions between factors which may affect habitat.
  4. Factors need to be assessed at the appropriate temporal and spatial scale. Some factors will require bay-wide or water mass level assessments, while others can be handled on much smaller scales (e.g., footprint level). It is helpful to describe effects along a distance scale. However, site-specific influences may change the units used on the scale (e.g., tens of meters versus hundreds of meters for the same types of environmental change).
  5. Monitoring programs are required to capture both temporal and spatial scale, as well as site-specific influences on habitat sensitivity. Moreover, this monitoring is particularly important where the regulatory framework is directed at protecting a specific habitat.
  6. Eelgrass is more sensitive habitat than kelp.
  7. Eelgrass and kelp habitat are sensitive to the following changes (Tables 3 and 4):
    - increases in pore water sulphide (eelgrass only);
    - nutrient loading (especially eelgrass; kelp limits are unknown);
    - formation of macroalgal mats, commonly *Ulva* / *Enteromorpha* (especially eelgrass; kelp limits are unknown);
    - low oxygen in the water column (especially eelgrass; kelp limits are unknown);
    - reductions in ambient light and shading; and
    - sedimentation.

These changes can be associated with finfish aquaculture (among other activities).

8. Guidelines for finfish aquaculture siting relative to eelgrass and kelp habitats are highly variable across the country. Current knowledge regarding the effects of aquaculture on these habitats is inadequate to demonstrate ecologically whether these guidelines are appropriate (i.e., current knowledge cannot demonstrate whether guidelines provide adequate protection).
9. The approach used in the working paper is useful and can be applied to determine the sensitivity of other marine habitat types to the potential effects of aquaculture.

Table 3: Factors affecting eelgrass, with threshold levels.

	ITEM	THRESHOLD AT WHICH EELGRASS BEDS MAY BE DAMAGED	REFERENCE
<b>Chemical Factors</b>			
Nutrient loading	Water column nitrate	5 to 10 $\mu\text{M NO}_3^- \text{N d}^{-1}$ ( <i>Zostera marina</i> )	Burkholder et al. 1994
	Pore water nitrate	20 mM (growth inhibition, <i>Z. marina</i> )	Peralta et al. 2003
	Pore water sulphide <sup>1</sup>	>70 $\mu\text{M H}_2\text{S}$ (growth reduction, <i>Z. marina</i> )	Terrados et al. 1999
	Pore water sulphide <sup>1</sup>	>800 $\mu\text{M H}_2\text{S}$ (photosynthesis reduced, <i>Z. marina</i> )	Goodman et al. 1995
	Nutrient loading <sup>1</sup>	30 kg N $\text{ha}^{-1} \text{yr}^{-1}$ (loss of 80 to 96% of <i>Z. marina</i> bed area)	Hauxwell et al. 2003
	Nutrient loading <sup>1</sup>	$\geq 60 \text{ kg N ha}^{-1} \text{y}^{-1}$ ( <i>Z. marina</i> beds gone)	Short and Burdick 1996; van Katwijk et al. 1999; Hauxwell et al. 2003
	Macroalgal canopy <sup>1</sup>	9 – 12 cm (decline in <i>Z. marina</i> )	Hauxwell et al. 2001
	<i>Enteromorpha</i> mat <sup>1</sup>	$\sim 4.5 \text{ kg wet wt m}^{-2}$ (50% reduction in biomass, <i>Z. capricorni</i> )	Cummins et al. 2004
Low oxygen	Water column $[\text{O}_2]$ <sup>1</sup>	<63 $\mu\text{M}$ ( <i>Z. marina</i> growth reduction)	Holmer and Bondgaard 2001
	Water column $[\text{O}_2]$ plus $[\text{H}_2\text{S}]$ <sup>1</sup>	<63 $\mu\text{M O}_2$ plus $\geq 100 \mu\text{M H}_2\text{S}$ ( <i>Z. marina</i> photosynthesis shut down)	Holmer and Bondgaard 2001
	Water column anoxia <sup>1</sup>	A few days ( <i>Z. marina</i> beds gone)	Plus et al. 2003
<b>Biological Factors</b>			
Herbivory	Rissoidae	>30 individuals per shoot ( <i>Z. marina</i> bed decline)	Fredriksen et al. 2004
	<i>Idotea</i>	$\sim 100$ individuals $\text{m}^{-2}$ ( <i>Z. marina</i> biomass loss)	Duffy et al. 2001
	seed and seedling predation by invertebrates	no threshold available at present	Wigand and Churchill 1988

<sup>1</sup> this item associated with effects of finfish aquaculture

Table 3: Continued

	ITEM	THRESHOLD AT WHICH EELGRASS BEDS MAY BE DAMAGED	REFERENCE
Bioturbation	<i>Dendraster excentricus</i>	~20 individuals m <sup>-2</sup> (prevents colonization by <i>Z. marina</i> )	Backman 1984
	<i>Neotrypaea californiensis</i>	100 individuals m <sup>-2</sup> (prevents colonization by <i>Z. marina</i> and <i>Z. japonica</i> )	Dumbauld and Wyllie-Echeverria 2003; Harrison 1987
	<i>Arenicola marina</i>	68 individuals m <sup>-2</sup> ( <i>Z. noltii</i> buried)	Philippart 1994
	<i>Hediste</i> [ <i>Nereis</i> ]	400 – 700 individuals m <sup>-2</sup> (excludes <i>Z. noltii</i> )	Hughes et al. 2000
Introduced species	<i>Carcinus maenas</i>	≥4 individuals m <sup>-2</sup> ( <i>Z. marina</i> )	Davis et al. 1998; David Garbary unpublished results
	<i>Musculista senhousia</i>	800 g dry mass m <sup>-2</sup> ( <i>Z. marina</i> rhizome inhibition)	Reusch and Williams 1998
	<i>Codium fragile</i> ssp. <i>tomentosoides</i>	no threshold available at present ( <i>Z. marina</i> )	Garbary et al. 1997
Pathogens	<i>Labyrinthula zosterae</i>	>50% of leaf blade ( <i>Z. marina</i> leaf production stops)	Ralph and Short 2002
<b>Physical Factors</b>			
Light <sup>1,2,3</sup>	% of surface light	<10% ( <i>Z. marina</i> )	Short et al. 1995
	μmol photons m <sup>-2</sup> s <sup>-1</sup>	<10 to 20 ( <i>Z. marina</i> )	Marsh et al. 1986; Peralta et al. 2003
	No light	Several weeks ( <i>Z. marina</i> beds gone)	Cabello-Pasini et al. 2002
Salinity and temperature	Salinity	>26 to 30‰ ( <i>Z. marina</i> )	van Katwijk et al. 1999
	Temperature	>25 to 30°C ( <i>Z. marina</i> )	Greve et al. 2003
Currents and scour	cm s <sup>-1</sup>	<16 ( <i>Z. marina</i> inhibition)	Fonseca and Kenworthy 1987; Koch 2001
	cm s <sup>-1</sup>	~ 25 (transition point for <i>Z. marina</i> )	Fonseca and Bell 1998
	cm s <sup>-1</sup>	>50 (inhibition of <i>Z. marina</i> )	Fonseca et al. 1983; Fonseca and Kenworthy 1987; Koch 2001
	cm s <sup>-1</sup>	>120 to 180 (max limit for <i>Z. marina</i> )	Fonseca et al. 1983; Fonseca and Kenworthy 1987; Koch 2001
Sedimentation <sup>1</sup>	depth of burial	≥25% of plant height (>50% mortality of <i>Z. marina</i> )	Mills and Fonseca 2003

<sup>2</sup> light calculations should add shading effect of epiphytes (i.e. take light measurement at true blade surface)

<sup>3</sup> salinity, temperature and nutrient status will affect light compensation levels

Table 4: Factors affecting kelps, with threshold levels

	ITEM	THRESHOLD AT WHICH <i>KELP BEDS</i> MAY BE DAMAGED	REFERENCE
<b>Chemical Factors</b>			
Nutrient limitation	water column nitrogen	$\leq 1 \mu\text{M l}^{-1}$ ( <i>M. pyrifera</i> )	Dean and Jacobsen 1986
Nutrient loading <sup>4</sup>	Nutrient loading	no threshold available at present	
	macroalgal canopy	no threshold available at present	
Low oxygen <sup>4</sup>		no threshold available at present	
<b>Biological Factors</b>			
herbivory	urchins	approximately 20 - 30 individuals $\text{m}^{-2}$ (‘barrens’ situation, exclusion of <i>Laminaria</i> )	Chapman 1981; Johnson and Mann 1993
	<i>Lacuna vincta</i>	~300 individuals per <i>Laminaria</i> thallus	Fralik et al. 1974
	<i>Tegula pulligo</i>	no threshold available at present ( <i>M. pyrifera</i> & <i>integrifolia</i> )	Watanabe 1984; Durante and Chia 1991; Sala and Graham 2002
	<i>Katharina tunicata</i>	no threshold available at present ( <i>L. groenlandica</i> )	Duggins and Dethier 1985
	<i>Peramphithoe stypotrupetes</i>	no threshold available at present ( <i>L. setchellii</i> )	Chess 1993
fouling organisms / introduced species	<i>Membranipora membranacea</i>	60-70% cover (one third blade loss in <i>M. pyrifera</i> )	Dixon et al. 1981
	<i>Membranipora membranacea</i>	>50% cover (defoliation of <i>Laminaria</i> bed)	Lambert et al. 1992
	<i>Membranipora membranacea</i>	% cover of sorus proportional to spore output loss ( <i>L. longicuris</i> )	Saier and Chapman 2004
	<i>Codium fragile</i> ssp. <i>tomentosoides</i>	no threshold available at present ( <i>Laminaria</i> )	Chapman 1999; Levin et al. 2002
	<i>Sargassum muticum</i>	no threshold available at present ( <i>L. groenlandica</i> )	Britton-Simmonds 2004

<sup>4</sup> this item associated with effects of finfish aquaculture

Table 4: Continued

	ITEM	THRESHOLD AT WHICH <i>KELP BEDS</i> MAY BE DAMAGED	REFERENCE
Pathogens	<i>Trichosphaerium sieboldi</i>	no threshold available at present ( <i>Laminaria</i> )	Rogerson et al. 1998
	'rot disease' bacteria	no threshold available at present ( <i>Laminaria, Macrocystis</i> )	North 1979; Meili 1991
	<i>Streblonema</i>	no threshold available at present ( <i>L. saccharina</i> )	Schaffelke et al. 1996
<b>Physical Factors</b>			
Light <sup>4,5</sup>	$\mu\text{mol photons m}^{-2} \text{ s}^{-1}$	<5 at 5°C <20 at 25°C ( <i>L. saccharina</i> )	Davison et al. 1991
	$\mu\text{mol photons m}^{-2} \text{ s}^{-1}$	<3 at 15°C ( <i>L. digitata</i> )	Rodrigues et al. 2000
	$\mu\text{mol photons m}^{-2} \text{ s}^{-1}$	<6 ( <i>M. pyrifera</i> gametophytes)	Deysher and Dean 1986
	$\mu\text{mol photons m}^{-2} \text{ s}^{-1}$	$\geq 700$ ( <i>L. saccharina</i> )	Bruhn and Gerard 1996
	$\mu\text{mol photons m}^{-2} \text{ s}^{-1}$	>800 ( <i>M. integrifolia, M. pyrifera</i> )	Graham 1996
Salinity and temperature	Salinity	<23‰ ( <i>M. integrifolia</i> range limit)	Druehl 1978
	Temperature	$\geq 20^\circ\text{C}$ ( <i>Macrocystis</i> )	North 1979; Druehl 1978; Deysher and Dean 1986
	Temperature	$> 25^\circ\text{C}$ ( <i>L. saccharina</i> )	Gerard and DuBois 1988; Davison 1987
Currents and scour	$\text{cm s}^{-1}$	<4 ( <i>M. integrifolia</i> )	Hurd et al. 1996
	$\text{cm s}^{-1}$	>300 (storm damage, <i>M. pyrifera</i> )	Graham et al. 1997
Sedimentation <sup>4</sup>	$\text{mg sediment cm}^{-2}$	$\geq 10$ (prevents spore attachment in <i>M. pyrifera</i> ) $\geq 108$ (smothers germlings of <i>M. pyrifera</i> )	Deviny and Volse 1978
	burial	stipe burial sometimes tolerated, blade burial not tolerated ( <i>Macrocystis</i> )	North 1979

<sup>5</sup> salinity, temperature and nutrient status will affect light compensation levels

## OVERALL CONCLUSIONS AND WAY FORWARD

### Overall Conclusions

1. The scientific foundations for management of the ecosystem effects of aquaculture are currently incomplete. However, in general the tools and approaches used by Habitat Management for site-specific management are consistent with the scientific information that is available.
2. A number of monitoring and modelling methods and approaches are available to support management. The main strengths and weaknesses of the individual tools are discussed in this report. However, for any of the tools to be a reliable guide to management, it is necessary that sound science practices be applied at all steps.
  - a. Monitoring programs should apply appropriate Quality Assurance / Quality Control standards in sampling, sample processing, and analyses.
  - b. Modelling approaches should be appropriately calibrated and validated for the conditions where the model is being applied.
3. For essentially all the indicators of effects that were examined, there is substantial variation in background levels on many space and time scales. This means it is neither possible nor appropriate to set uniform industry-wide operational thresholds intended to trigger management actions. However, consistent *approaches* with regional or local quantitative thresholds are possible.
4. The use of multiple measures of ecosystem status and change will usually be the most effective strategy for management of ecosystem effects of aquaculture. Multiple measures are recommended because each single measure, as well as the suite of measures, is likely to be affected by a variety of sources of variation other than effects of aquaculture.
5. The management tools and approaches currently in use are focused primarily on near-field (beneath to <50 meters from a netpen) and site-specific regulatory applications. This review found several indications that there may be far-field (>500 meters to local bay-scale) cumulative effects, such as increased dissolved nutrients, possible changes in macroalgal communities and increased sedimentation in areas where there are high densities of aquaculture operations. Although various regional initiatives are underway, currently there is no comprehensive program to manage these far-field effects. Accurately quantifying and managing them will require new or modified approaches and tools, make extensive use of modelling and spatial analysis (mapping), be most practical at the planning stages in a developing industry, and requires an integrated approach to management.
6. New tools which are proposed for use in management of environmental effects of aquaculture should only be adopted broadly once their performance characteristics, including sensitivity, specificity and cost-effectiveness, are known.
7. A cooperative approach, including government, industry and other stakeholders, is preferred for assessing performance characteristics of both new and established management tools and measures of the environmental effects of aquaculture. The cooperative approach should extend to full sharing of the information package necessary to assess the ecosystem effects of the aquaculture facilities in an area.

8. The analyses and models discussed throughout this report are intended to describe the nature and likelihood of changes in ecosystem properties. Interpretation of results may identify ecological conservation concerns, but they do not and should not include judgments of the societal value of those changes. It is the overall management approach that should take account of ecosystem properties of social, cultural or economic importance, as well as the scientific advice on the ecosystem consequences of human activities.

## **The Way Forward**

Two of the Overall Conclusions provide a basis for the way forward with present knowledge. First, although the scientific foundations for management of the ecosystem effects of aquaculture are currently incomplete, the tools and approaches used by Habitat Management for site-specific management are consistent with the scientific information that is available. However, given the number of scientific uncertainties identified above and the large fraction of them for which additional research, often collaborative with industry, is likely to increase our knowledge, management practices will have to be adaptive as knowledge accumulates. This will be particularly the case for management of far-field and cumulative effects, if evidence continues to accumulate suggesting such management would be appropriate.

Second, for essentially all the indicators of effects that were examined, there are substantial variations in background levels on many spatial and temporal scales. This variability means it is neither possible nor appropriate to set uniform industry-wide operational thresholds intended to trigger management actions. However, consistent *approaches* with regional or local quantitative thresholds are possible. Substantial research, analysis, modelling and monitoring will be needed to set the regional and local quantitative thresholds, and to show that the local and regional thresholds are, indeed, reflective of a consistent national approach.

For both of those reasons, is it likely that national review and advisory meetings, such as the one which resulted in this Science Report, would be useful on a periodic basis. The format of balanced inclusion of researchers, managers from various levels of government, industry participants and members of public interest groups should be continued.

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