Salmon Farming Dialogue

Benthic Working Group Report

Kenneth D Black – Scottish Association for Marine Science Oban
Pia Kupka Hansen – Institute for Marine Science, Bergen
Marianne Holmer – University of Southern Denmark, Odense

Report is still open!

- I intend to update the report after this meeting.
- I intend to deliver the final version in ~2 weeks

Contents

0. ToR

Objectives

- Review status of current research and understanding of issues
- Identify significant gaps and/or areas of disagreement
- Identify key research groups
- Identify existing research efforts in the area
- Suggest scope, timeframe and cost for addressing gaps, including draft TORs for key research needs

Impacts of salmon farming on the benthos

- Indicators of impact on benthos
- Factors affecting the range and degree of benthic impacts
- Cumulative and synergic impacts of multiple activities
- Potential for management protocols such as fallowing to mitigate benthic impacts
- Other mitigation methods and methods of seabed management and their effectiveness
- In dispersive areas, are their factors that might allow accumulation of wastes at a distance from their origin?
- How good are models of impact?
- What are the relative merits of regulating on benthic disturbance compared to regulating on the basis of feed inputs?
- Cumulative impacts – how much benthos are we prepared to lose in a basin from multiple stressors?
- Which other sources of organic matter might be important?
- How significant is habitat degradation, and consequent loss of ecosystem function?

Siting

- Site-selection as a means to minimize key impacts.
- What characteristics contribute to a benign site?
- Coastal zone management and marine spatial planning
  - Managing multiple users, protect key ecological areas, designated no-farming zones. Are there types of benthos/bottom where farming is not ecologically appropriate?
  - What methods are there for defining the appropriate scale or limit of intensive fish farming in a water body? (e.g. oxygen levels on the benthos)
  - Do different regions have different impact thresholds?

- **For both benthic impacts and siting areas examine/consider:**
- Identification of issues that industry will have commercial motivation to address and issues where this is not the case
- Differences from region to region
  - Understanding underlying differences
  - Sharing learning
- Suggest indicators that could be used to measure benthic impacts or siting issues.
- Trends and causes of improved performance over time e.g. industry and regulatory initiatives.

1. Introduction

- The Atlantic salmon *Salmo salar* is the predominant culture species in temperate marine waters. Production is almost exclusively from floating cages, an open system.

- Inputs are: juvenile fish; fish feed; medicines; disinfectants and anti-foulants, and the outputs (losses) are: harvested fish; mortalities, escaped fish; uneaten feed; faeces; excreted metabolic wastes; and effluent chemical species e.g. medicines.

- These outputs can participate in external biological, chemical and ecological systems where they may cause unwanted effects. These effects are often complex, varying by orders of magnitude on temporal and spatial scales.

- Regulation of salmon cage culture is largely driven by the potential for disruption of the benthic ecosystem, even though effects on the benthos may not be the most ecologically significant associated with fish farming.

- This is because the effects may be profound and are relatively easy to detect and quantify, both in severity and spatial extent, at all but the most energetic sites where resuspension is a dominant physical process.

- Effects on dissolved nutrient concentrations, sea lice transmission to wild populations, escapes, and medicines/chemicals may be more ecologically significant, but the links between cause and effect are hard to quantify and, therefore, often controversial.

- Benthic effects, unlike algal blooms for example, are generally easy to attribute to the fish farm and, therefore, are amenable to scientifically robust and quantitative regulation.

- There is a large body of peer-reviewed publications on the processes of benthic pollution at fish farms

- Significant research has been carried out and published in all the major salmon farming countries except Chile where very few studies are currently available.

- While the scientific processes are likely to be broadly predictable, the degree and extent of local impacts in Chilean farms will depend on local factors and further study is required.

2 Benthic community and sediment biogeochemistry

- Macrofauna are operationally defined as those sediment dwelling organisms that are retained on a 500µm sieve.

- Benthic macrofaunal communities in sediments receiving normal detrital inputs derived from planktonic production in the overlying water column are species rich, have a relatively low total abundance/species richness ratio and include a wide range of higher taxa, body sizes and functional types, i.e. they are highly diverse communities (Pearson, 1992).

- The total productivity of the system is dependent on the availability of food, organic matter, and its quality.

- Macrofauna have evolved to maximise the utilisation of the available resource by virtue of a wide range of feeding modes and some species can vary their mode of feeding depending on environmental factors.

- Benthic types include
  - filter feeders that gather detrital material from the water column above the sediment,
  - surface deposit feeders that feed on material deposited on the sediment surface,
  - sub-surface deposit feeders that consume buried organic material by burrowing, and
  - carnivores that prey on other macrofauna.

- Microbes degrade organic material and are themselves consumed by macrofauna, mediating the transfer of nutrients up the food chain.

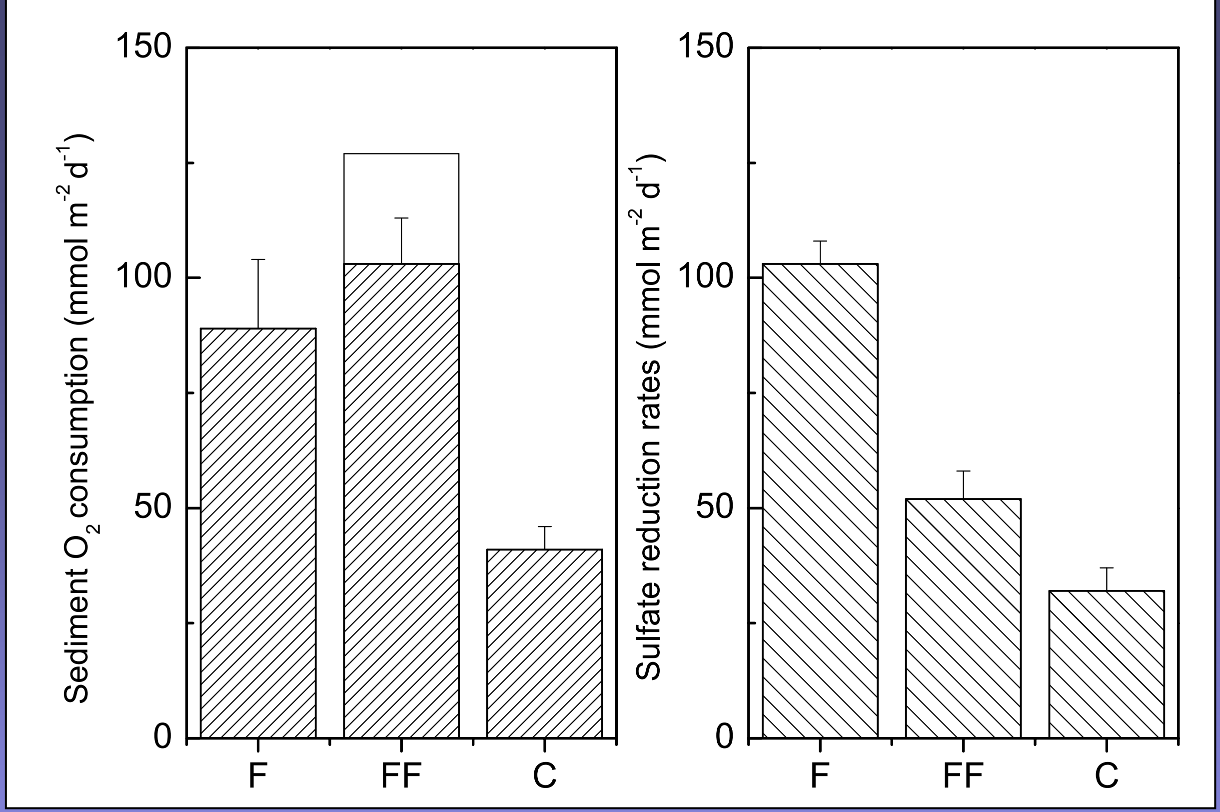
Oxidation of Organic Matter OM

- aerobic respiration, ammonium oxidation (to nitrite) and nitrite oxidation (to nitrate). These aerobic nitrifying processes are inhibited by sulphide and are, therefore, of limited importance in sediments beneath marine fish farms;
- denitrification (producing dinitrogen from nitrate);
- nitrate reduction (producing ammonium from nitrate) and manganese reduction;
- iron reduction;
- sulphate reduction (producing hydrogen sulphide)
- and lastly, under the most reducing conditions, methanogenesis (producing methane).

- Bioturbation is that process of sediment mixing by animals that may expose new substrates to microbial action and allow the movement of oxidants by active or passive pumping of water through burrows, a process known as bio-irrigation (Nickell *et al.*, 2003).

- Heilskov et al (2006) found that irrigation rate was directly correlated with organic degradation rate and that irrigation velocities increased with organic matter loading, indicating greater fauna-induced oxidation in more enriched environments.

- This implies that a change in faunal structure in fish farm sediments towards smaller opportunistic polychaete species (with lower irrigation potential) will result in slower mineralization rates and, therefore, increased accumulation of organic wastes.



Sediment oxygen consumption (left) and sulphate reduction rates (right) at a fish farm site (F) and a control site (C) showing the high activity at the fish farm due to organic matter loading of the sediments. Fauna (the polychaete *Nereis diversicolor*) was added to the fish farm site (FF) and the measurements showed **increased** oxygen consumption enhanced due to re-oxidation of sulphides and animal respiration (open bar). Sulphate reduction rates **decreased** due to oxidation of the sediments generally improving the sediment conditions.

- The redox potential (Eh) profile measured down the sediment column to a depth of 10-15 cm gives a useful guide to the relative degree of carbon enrichment in the sediments (Pearson & Stanley, 1979)

- Positive Eh values are indicative of aerobic and oxidized conditions whereas negative values are associated with anaerobic microbial processes and reduced conditions.

- Under “normal” rates of detrital carbon input to sediments, the redox discontinuity level (RDL), i.e. the point at which anaerobic processes become predominant, lies some centimetres below the surface.

- As carbon inputs increase so does Biological Oxygen Demand (BOD) and the RDL approaches ever closer to the sediment surface. Eventually, under very high detrital inputs, the RDL coincides with the sediment/water interface, where, under low flow conditions, it might even rise into the water column.

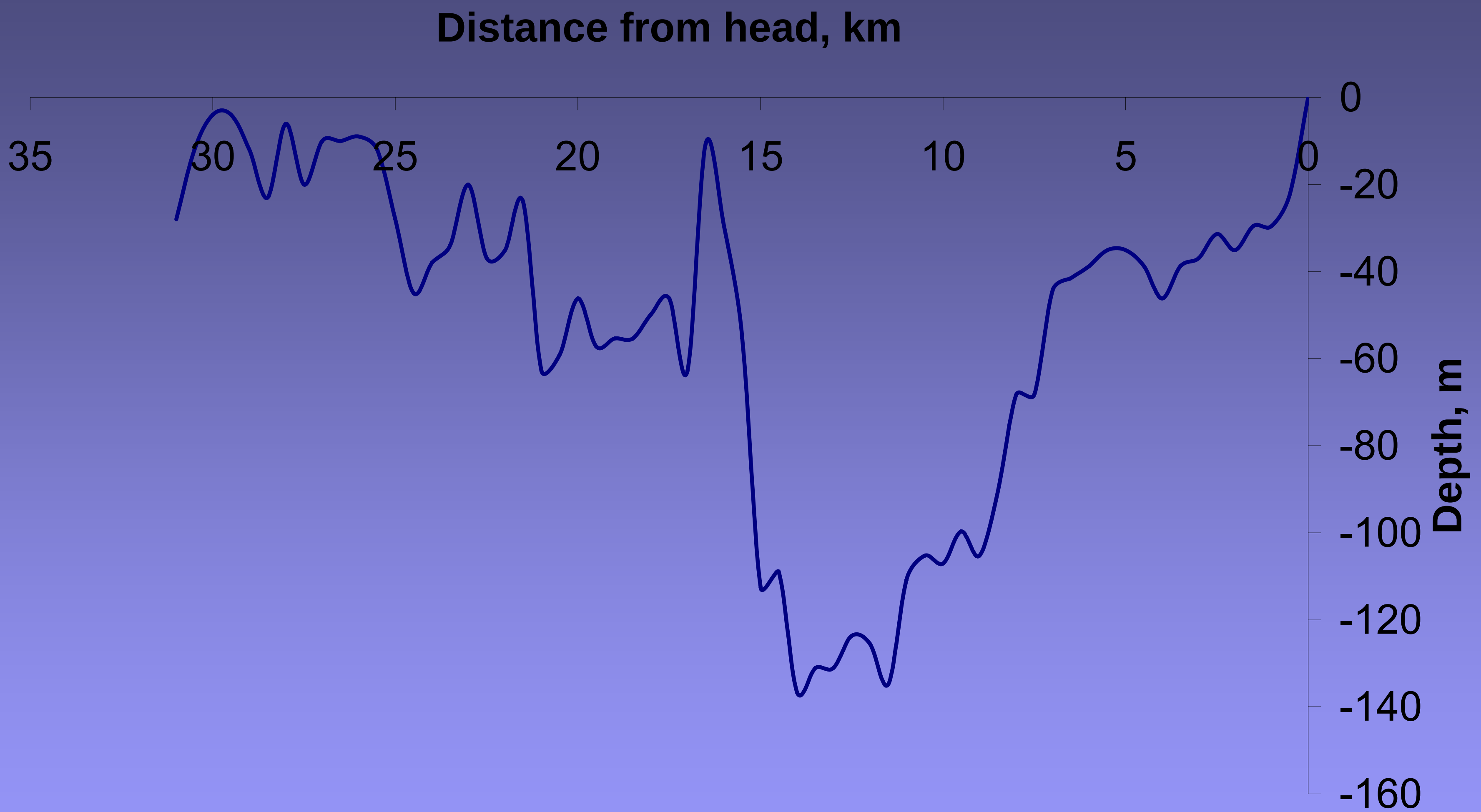
- A sign of anoxic sediments is a cover of the sulphide oxidizing bacteria *Beggiatoa* sp., which form a white mat on the sediment surface. These bacteria derive energy from the oxidation of sulphides from the sediments with oxygen from the water column and, although the bacteria are transparent, the mat appears white due to the precipitation of elemental sulphur inside the bacteria.

- Eventually, if oxygen is depleted in the water just above the sediment surface, the sediment appears black from precipitates of iron sulphides, and a white cloud in the overlying water indicates the zone where sulphide diffusing from the sediments meets the oxic water column.

- Highly organically enriched sediments can occur naturally from large marine or terrestrial inputs of OM. This may be transient and localised or long-lived and wide scale.

- Hypoxia/anoxia in sediments and overlying water occurs when the supply of new oxygenated water is poor as may be the case, for example, in deep silled fjordic systems.

- In such systems, benthic communities are modified and specialist opportunist animals may dominate.



Distance from head, km
35
30
25
20
15
10
5
0
0
-20
-40
-60
-80
-100
-120
-140
-160
Depth, m

3 Sources of perturbation

- 2 main sources:
  - wasted (i.e. uneaten) feed and
  - faecal material.

- Feed wastage occurs in pulses associated with feeding events, and increases towards the end of a meal as the fish approach satiation.

- Feedback systems may be operated at modern salmon farms including video cameras under the cages and sediment traps with particle sensors. These systems reduce feed input during meals on the detection of feed particles passing to the bottom of the cage.

Feed wastage

- Early estimates of feed wastage (Gowen & Bradbury, 1987) of up to 20% have been superseded and current estimates are of the order of 5%. This value is difficult to verify, and feed wastage is rarely measured in the field.

- Farmers have a strong interest in keeping this to a minimum, as feed is costly and farmers may be judged on the food conversion ratios (FCR) of their crop, which is dependent on low feed wastage: 5% has become an accepted estimate in Scotland.

Waste feed portion (%)		
20	Estimated	Gowen et al. (1989)
5–11	Calculated	Findlay and Watling (1994)
5	Applied	Panchang et al. (1997)
5–15	Observed/estimated	Pearson and Black (2001)
0 and 3	Estimated	Cromey et al. (2002a)
10	Mass balance calculations	Pérez et al. (2002)
5 or less	Estimated	Brooks and Mahnken (2003)
8	Calculated average from Findlay and Watling (1994)	Stucchi et al. (2005)
3	Applied—from estimates given in Cromey et al. (2002a)	Corner et al. (2006)
15	Mass balance calculation	Strain and Hargrave (2005)

Chamberlain, J. and Stucchi, D. (2007). Simulating the effects of parameter uncertainty on waste model predictions of marine finfish aquaculture. *Aquaculture* 272, 296-311.

Fragmented pellets

- Automated feeding systems can provide better control over feed wastage
- Systems which blow feed through long pipes from a central hopper can also fragment and erode pellets before they reach the fish.
- The fine fragments and dust so produced is seen as a scum on the water surface and on cage structures.
- Fragments that enter the water and sink may be too small to be ingested by fish.
- However, efforts have been made to understand the processes of pellet breakage (Aarseth et al., 2006) and design systems to reduce this.

Food Conversion Ratio

- Economic FCR = Amount of feed given / (Biomass(BM) Harvested + BM in the water at end of period – BM at start of period)

- Biological FCR = Amount of feed given /(Biomass (BM) Harvested + BM in the water end of period + BM Mortalities + BM Discarded + BM Loss – BM at start of period)

Wet and dry

FCRs typically quoted for moist feed input (~9% water) and wet fish output (~75% water)

Dry weight FCR is 3.6 times higher

FCRs of 1 or less are achievable (much lower than other marine fish species)

Mass balance

- Feed = Growth + Metabolism + Uneaten Feed + Faeces
- Only Feed and Growth are easy to measure.

FCR for Norwegian Atlantic Salmon farms (Myrseth, 2005).

Year	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
FCR	1.18	1.19	1.09	1.20	1.23	1.20	1.20	1.20	1.21	1.28

Scottish production (FRS, 2007), feed used, mortalities (all kg), apparent FCR, FCR including mortalities

	Production	Feed used	Mortalities	Apparent FCR	FCR Including mortalities
2005	129,588,000	174,983,395	6,553,946	1.35	1.29
2006	131,847,000	187,831,476	8,385,750	1.42	1.34

But
Apparent FCR ≠ EFCR
FCR inc morts ≠ BFCR
As we do not know the biomass at the beginning and end of the year

	Production	Feed used	Mortalities	Apparent FCR	FCR Including mortalities
2005	129,588,000	174,983,395	6,553,946	1.35	1.29
2006	131,847,000	187,831,476	8,385,750	1.42	1.34

Optimal FCR	Feed used for growth	Feed not used for growth	%
1.1	149,756,140	25,227,255	14.4
1.1	154,256,025	33,575,450	17.9

Implication is that either FCR is higher than 1.1 or feed losses are higher than 5%

- Is FCR decreasing owing to increasing substitution of less digestible vegetable material? (Mundheim et al., 2004; Young et al., 2005).
- Bottom line is that waste feed and faecal outputs are not well constrained
- Research gap!

Faecal losses

- Faecal material is produced in post-prandial pulses. Its amount is related to the digestibility of the feed: modern diets are highly digestible (~85%). **Need better data.**

- The settling velocity spectrum of salmon faeces from a range of fish sizes is well characterised (Chen et al., 1999a; Chen, Beveridge & Telfer, 1999b; Chen et al., 2003; Cromey et al., 2002a).

Particle distribution on seabed

- The distribution of wasted feed and faecal particles will depend on the depth and the current speed: the greater the depth and the greater the currents, the larger the impacted area but the lower the degree of impact.

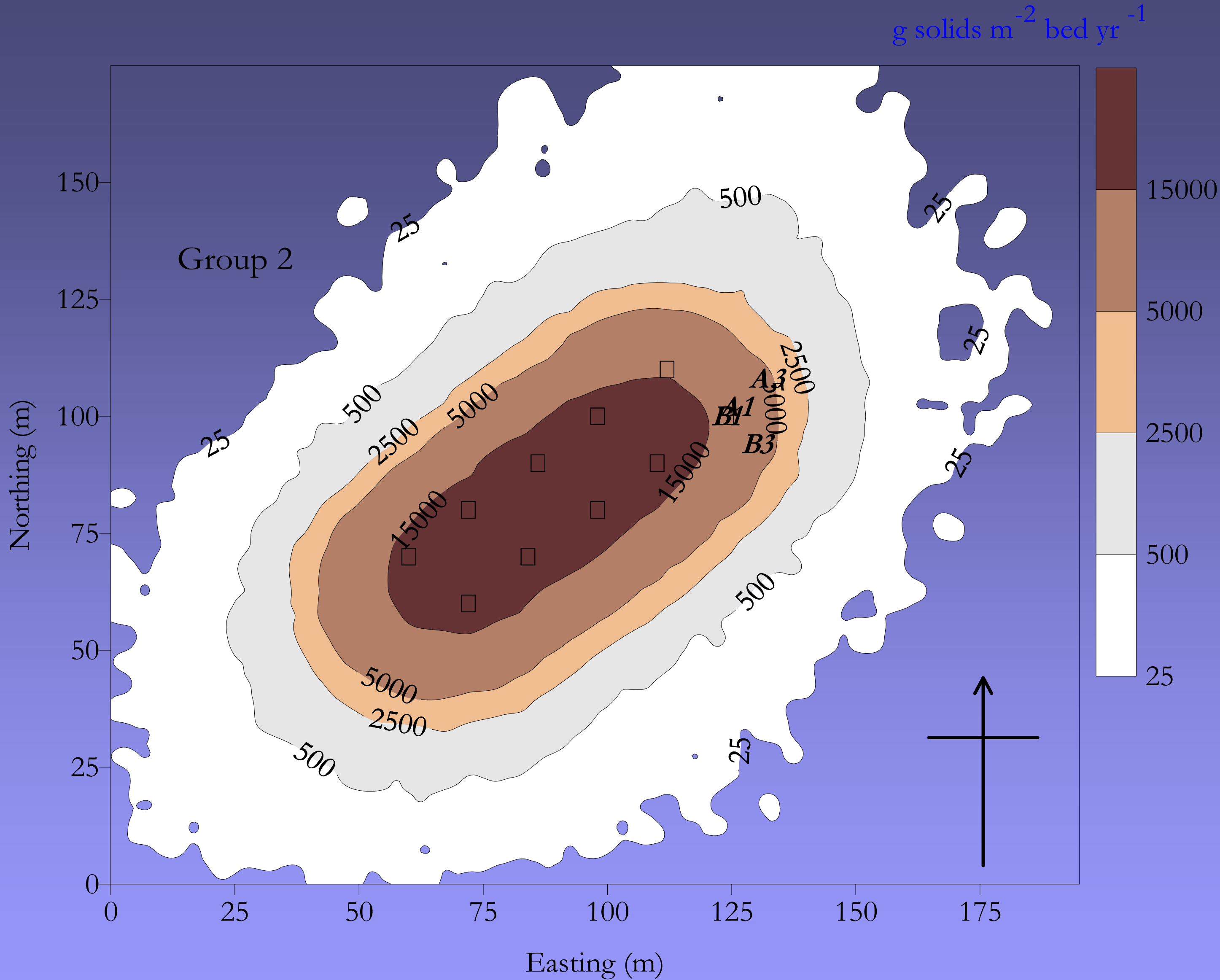
- Once on the bed, particles may be eroded by bottom currents: where such currents are very strong, all of the particles can be advected away from the farm; where currents are very weak, the majority of the particles accumulate where they are deposited.

- In flume experiments, waste pellet accumulation enhances the erosion of natural sediments (Neumeier et al., 2007) by preventing the development of a stabilising diatom biofilm - although in turbid natural waters with low light penetration this effect may be less important.

- The critical resuspension velocity has been estimated at about 9 $cm.s^{-1}$ (Cromey *et al.*, 2002b).

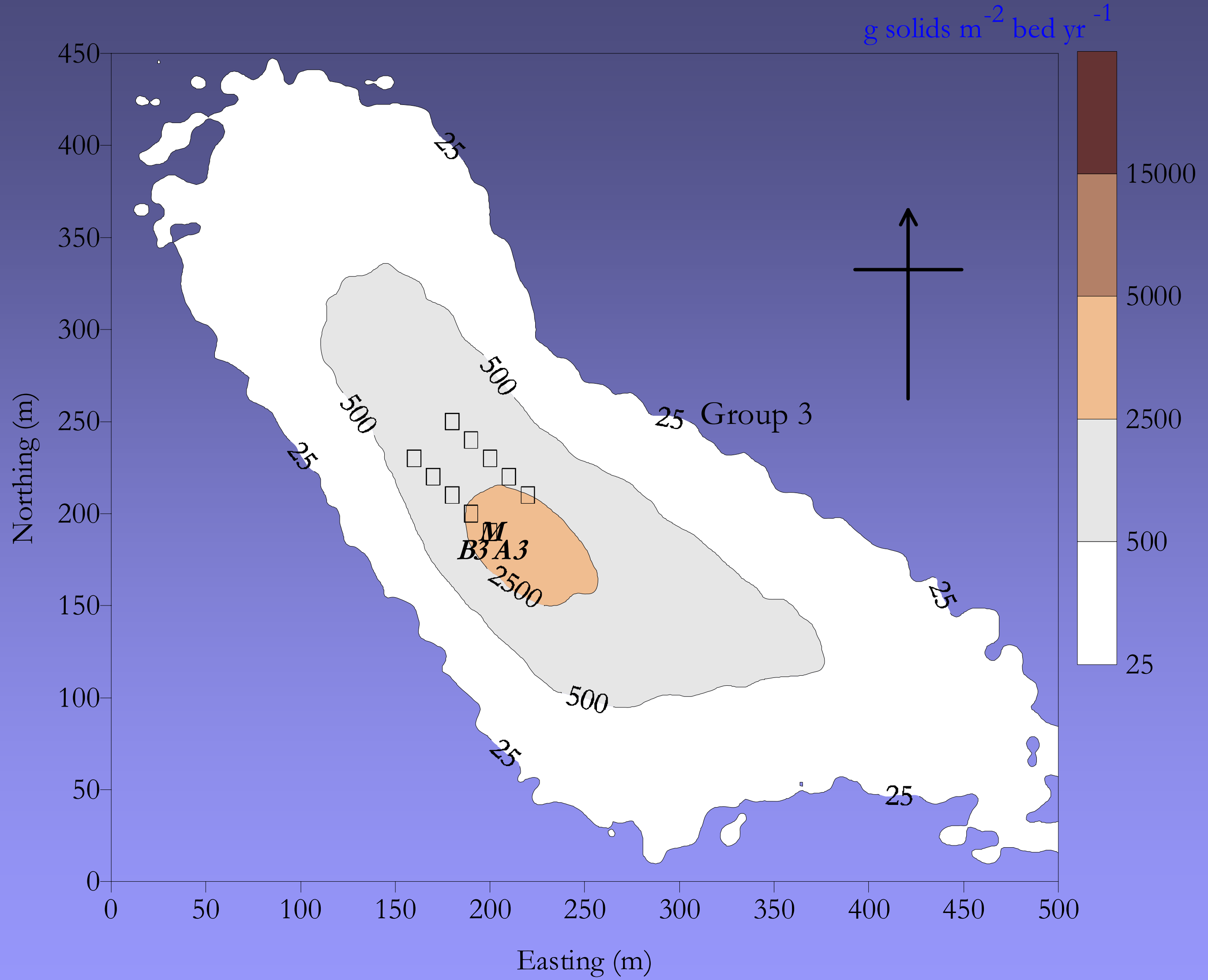
- At all but very quiescent sites, near-bed currents are periodically higher than this and it is likely that considerable amounts of the vertical flux will be transported away from the farm.

- This is in accord with estimates by Strain and Hargrave (Strain & Hargrave, 2005) who found at a dynamic site that the majority of the carbon flux could not be accounted for in terms of the benthic oxygen demand.



Key

- cage centres


g solids m^{-2} bed yr^{-1}
15000
5000
2500
500
25
Group 3
500
2500
M
B3 A3
Northing (m)
Easting (m)
0
50
100
150
200
250
300
350
400
450
500

Key

- cages

Can particles accumulate away from the site?

- The advective processes that carry particles to the sea bed and later resuspend them are always accompanied by turbulent diffusion caused by random fluctuations in current speed and direction.

- These diffusive processes make it statistically highly improbable that particles will re-concentrate at distance from the farm.

- An exception to this might be where there is some area down-stream of the farm where current speed is severely attenuated. This could be in the form of a physical feature such as a seabed depression or a change in the substratum that increases the benthic boundary layer depth.

- For example, a maerl bed may trap waste particulates within its structure (Hall-Spencer *et al.*, 2006). Thus, even in dispersive areas it is necessary to consider changes in the benthic environment at a distance from the farm which may trap particulate wastes and interfere with the normal diffusive processes.

- The distribution of cages within a farm is also an important factor affecting flux rate per unit area as the depositional footprint of closely spaced cages may overlap. Simulations have shown that the carrying capacity of a fish farm site may double when the cages are scattered compared to when they are situated close together in one unit (Stigebrandt et al. 2004).

Currents

- Predicting the fate of particulate wastes from fish farms is dependent on being able to describe accurately the hydrodynamic processes that advect particles from the cages to the seabed and also may remobilise such particles by resuspension.

- Presently, the Scottish consenting process relies on a 15-day current meter record, from several depths, but at a single fixed point close to the fish farm location (www.sepa.org.uk).

- This is thought to be the best balance between cost and fitness-for-purpose for sites located in relatively quiescent waters.

- This is because at such sites a large proportion of particles are retained within a few hundred meters around the farm and so their advection may realistically be described by the measured current record.

- As sites become larger, they typically require location in more dispersive areas in order to meet Sediment Quality Standards and other Consent conditions. Increasingly greater proportions of particles are advected outside the area that can be reasonably described by a single current record and benthic impact predictions become unreliable owing to uncertainties in the hydrodynamics.

- The 15-day record requirement was originally chosen in Scotland as this represents one spring-neap tidal cycle and thus should capture a significant proportion of the variability due to tides.

- However, in many instances of place and time, tides are not the dominant driver of local currents in the marine environment. Scaling up a 15 day record to an annual record, even while compensating for variations in the strength of the Spring-Neap cycle through the year, can magnify deficiencies in an unrepresentative record.

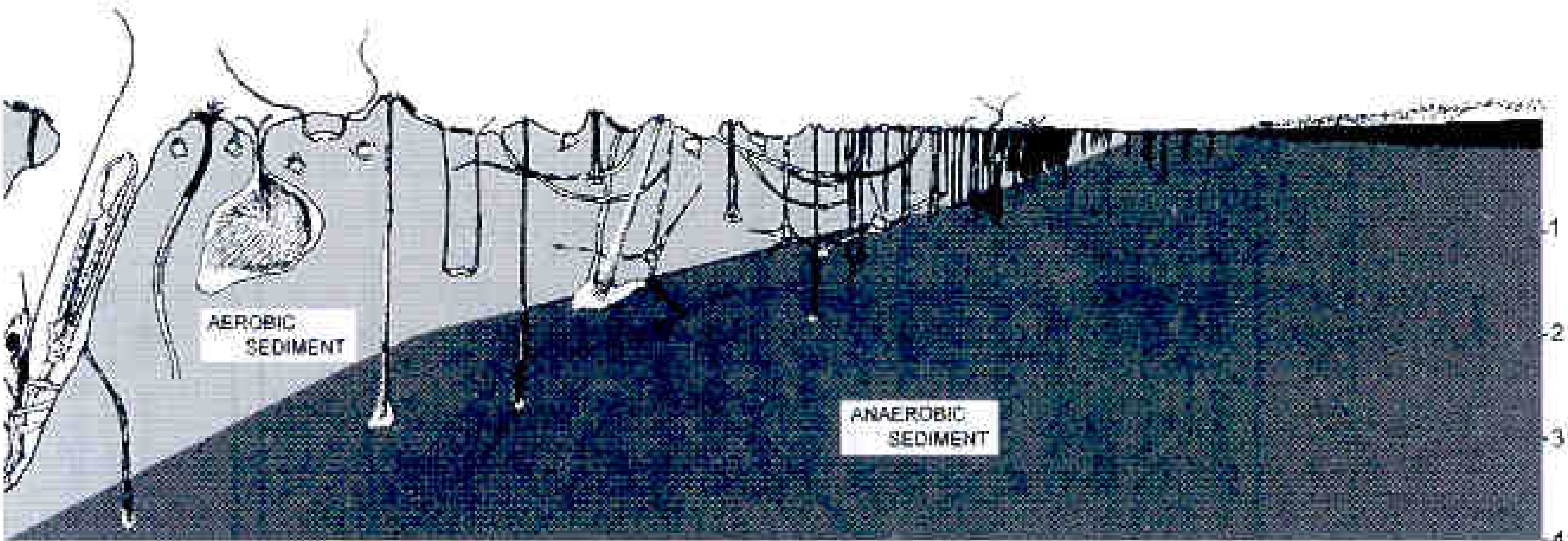
- A 206 day record from a Scottish fish farm was analysed for variability in summary statistics for 15-day blocks (Cromey & Black, 2005). There was high variability between 15-day blocks and the mean.
- The data used for the consent were from a separate record which showed the lowest mean surface currents and intermediate mean near-bed currents.
- The long data set shows that this site is actually more dispersive than the data used in the consent (but this will not always be the case).

	Surface mean cm s^{-1}	**Near bed mean cm s^{-1}**
Whole record	10.6	5.9
Most dispersive 15 days	14.8	9.6
Least dispersive15 days	6.4	2.0
Used in consent	2.7	3.8

Hydrodynamic models are the way to go!

- The best available solution to these problems is the use of a hydrodynamic model rather than a single current record to drive the model.
- This allows the simulation of the current field in space and time.
- Hydrodynamic models have in the past been seen as too expensive for fish farm applications but the situation is changing rapidly with access to increasing computing power at lower cost.

4 Consequences of organic particulate inputs to sediments



ZONE	NORMAL	TRANSITORY		POLLUTED	GROSSLY POLLUTED
TYPICAL MACROFAUNA DOMINANTS	Nucula Amphiura Terebellides Rhodine Echinocardium Nephrops	Labidoplax Corbula Goniada Thyasira Pholoe	Chaetozone Anaitides Pectinaria Myriochele Ophiodromus	Capitella Scolelepis	No macrofauna Surface covered by fibre 'blanket'

Souring

- In the 1990's, the size of individual farms increased rapidly from a few hundred tonnes to up to and over a thousand tonnes.
- But farms were often located in the very sheltered environments required by the previous generation of largely wooden cage collars, and some farms became so polluted that total sediment azooia occurred, and there is more recent evidence of this from the expanding Chilean industry (Mulsow et al., 2006).
- Such farms were prone to outgassing of methane, carbon dioxide and hydrogen sulphide – a process that has been termed "souring".
- Hydrogen sulphide is highly soluble and, although it is rapidly oxidised over a few hours, measurable concentrations could be detected in waters overlying the sediments (Black, Kiemer & Ezzi, 1996a; Black, Kiemer & Ezzi, 1996b).
- Hydrogen sulphide is highly toxic to fish (Kiemer *et al.*, 1995) and has been implicated in both fish kills, and reduced performance, but a causal link is difficult to prove as pathologies are non-diagnostic for hydrogen sulphide poisoning.

Scavengers consume waste feed

- A recent, and as yet unpublished, study around salmon farms in Norway indicated that >80% of the diet of saithe around farms was lost food pellets. Cod diets around farms were also modified compared to control fish, although they were less reliant on lost feed (30% of diet) (T. Dempster, pers. com.).

Recovery

- *chemical* – "defined as the reduction of accumulated organic matter with a concomitant decrease in free sediment sulfide and an increase in sediment redox potential under and adjacent to salmon farms to levels at which more than half the reference area taxa can recruit and survive (free sulfides < 960 μM)"

- *biological* – "defined as the restructuring of the infaunal community to include those taxa whose individual abundance equals or exceeds 1% of the total invertebrate abundance at a local reference station. Recruitment of rare species representing < 1% of the reference abundance was not considered necessary for biological remediation to be considered complete. As an example, if the mean reference station total abundance was 8000 macrofauna/m^2, then all of those taxa with a mean abundance of ≥ 80 animals/m^2 would be considered necessary for biological remediation to be considered complete."

Several recovery studies – Scotland, Canada, Tasmania

- MacLeod and co-workers have studied recovery processes at salmon farms in Tasmania over several years and have reached some interesting conclusions:
- 1) macrobenthic recovery was slower than chemical recovery, so chemical methods were not sufficient to define ecological recovery (Macleod, Crawford & Moltschaniwskyj, 2004)
- 2) recovery of macrobenthic community function (from analysis of life history attributes of dominant fauna) is more rapid than return to community equivalence, and may be a more useful measure of benthic recovery (Macleod et al., 2007)
- 3) macrobenthic recovery was faster at a more quiescent site than a more exposed site attributed to the greater resilience of the species typically found at such sites and differences in larval supply (Macleod, Moltschaniwskyj & Crawford, 2006).

Recovery time

- Significant chemical recovery occurs relatively quickly, as labile organic carbon is degraded over a few months.
- Biological recovery may take years depending on the site.
- Increased by Slice??
- Increased by copper??

Benthic effects in Chile

- There are few published reports on benthic impacts from Chile ((Buschmann et al., 2006; Mulsow et al., 2006; Soto & Norambuena, 2004), which is a significant issue given the rapid expansion of that industry.

- Research needed!

Indicators of benthic and sediment effects

- The use of indicators of ecosystem state is widely proposed. Gallopin (1997) gives a definition of an indicator as *"An operational representation of an attribute (quality, characteristics, property) of a system"*.

- In the ECASA project (www.ecasa.org.uk) several indicators relating to aquaculture-environment interactions have been assessed

  including both benthic and sediment indicators.

www.ecasa.org.uk/toolbox

Benthic indicators

AMBI

Benthic trophic group

Biomass fractionation index

ITI

Macrofauna presence

Meiofauna sediment test

Meiofaunal diversity

Multivariate indices

Univariate indices

Sediment indicators

Ammonia in pore waters

Carbon quality (Rp index)

Heavy metals

MUFAB

Nitrifier bacteria

Oxygen consumption fluxes

Phosphate in pore waters

Redox Eh

Sediment flux (traps)

Sulphate and ammonia gradients

Sulphide/oxygen probe

Total Nitrogen (surface)

Total Organic Carbon

Total Organic Carbon (surface)

Total Phosphorous (surface)

- No single “magic-bullet” indicator exists. Rather a suite of indicators must be evaluated in order to correctly interpret the sediment state: if an inappropriate indicator set is chosen then it is quite possible to draw misleading conclusions (Mulsow et al., 2006).

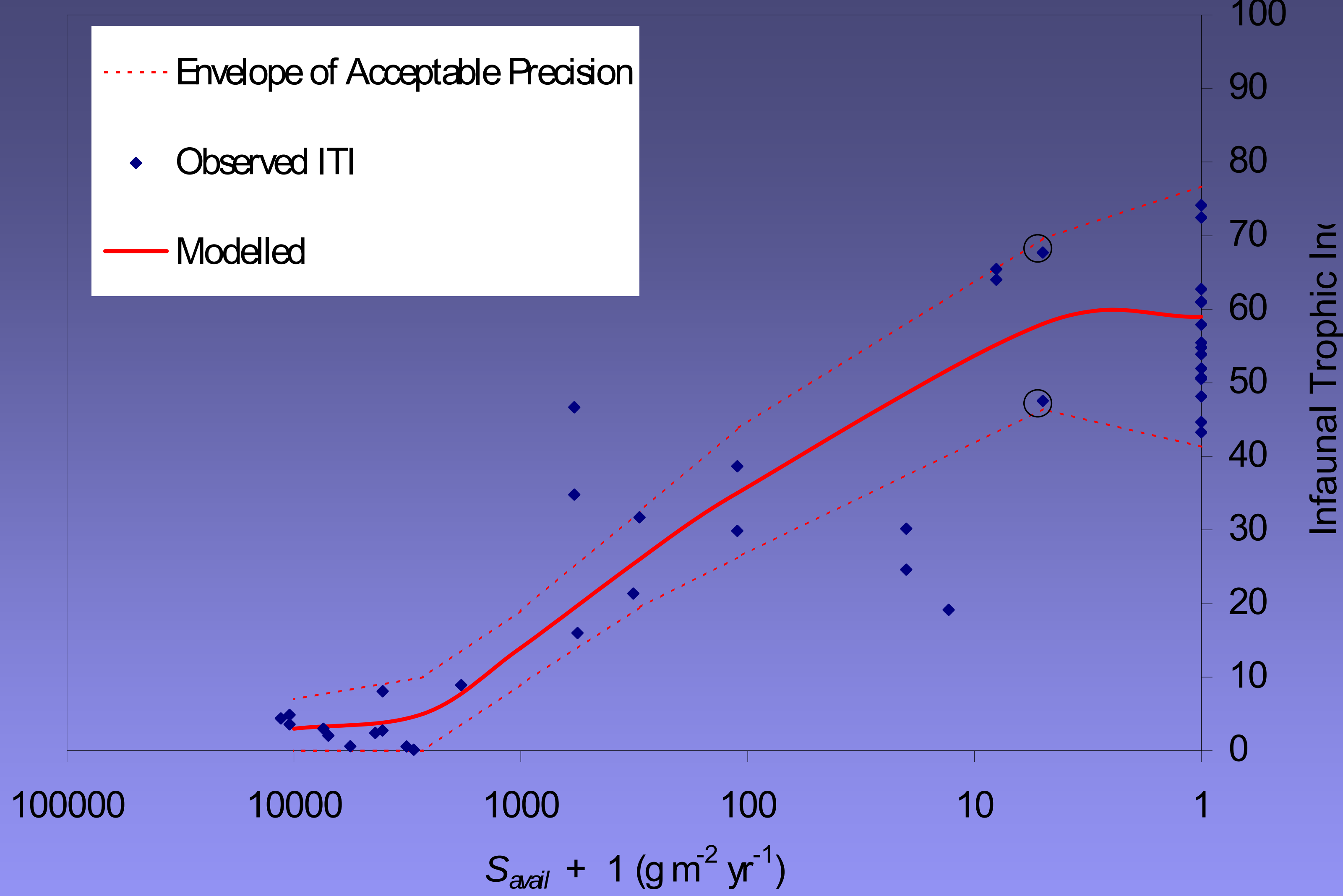
- A wide range of sediment indicators are used in regulation of aquaculture (section 6) with different legislators choosing different indicator suites.

- Although this is unfortunate in that it often does not allow direct numerical comparison between countries, in general, similar qualitative information on sediment state (i.e. position on the Pearson –Rosenberg continuum) can be derived if a sufficiently broad range of indicators have been evaluated.

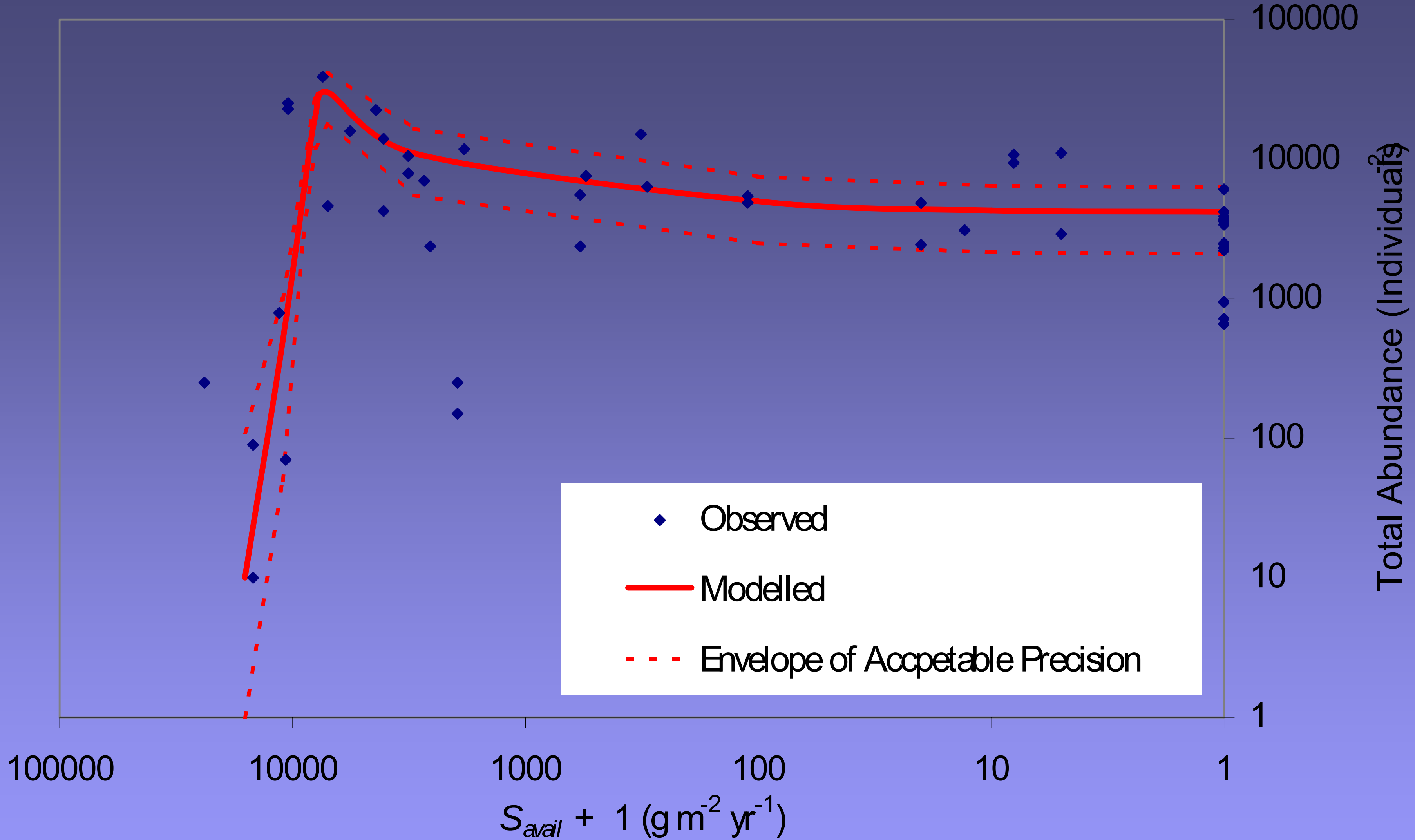
5 Modelling impacts

- Several models exist for the estimation of benthic impacts around fish cages (Cromey & Black, 2005). In general, modelling of the physical processes is relatively well understood.

- However, biogeochemical aspects, including the degradation of organic carbon and the behaviours of benthic animals (e.g. bioturbation) are much harder to model (**Research Need**) and so ecological outcomes (and biogeochemical indicators) are generally predicted via empirical relationships between predicted organic matter accumulation and some ecological index.



DEPOMOD modelled solids accumulation (*Savail*) plotted against observed Infaunal Trophic Index. Circles demonstrate the variation in the benthic composition of duplicate grabs and the Envelope of Acceptable Precision is defined to take account of this natural variation (88% of stations in EAP, n = 42 stations).



DEPOMOD modelled solids accumulation (*Savail*) plotted against observed total abundance. Envelope of Acceptable precision is shown by the dashed line (68% in EAP, n=50).

- At accumulation rates greater than 10 kg m^{-2} yr^{-1}, highly significant effects on the benthos must be expected. Experience has shown that accumulation rates of 25 kg m^{-2} yr^{-1} and above are likely to lead to extremely modified conditions with few or no animals.

- DEPOMOD has recently been tested in Canada (Chamberlain & Stucchi, 2007) who found that the existing parameterisation for resuspension of waste feeds was unsatisfactory and led to considerable deviation between model prediction and observation at a highly energetic site.

- In this case, the critical erosion threshold of 9.5 cms-1, which is based on a field experiment designed to study the resuspension of faecal material but not waste feed (Cromey et al., 2002b), resulted in model simulations advecting all of the deposited particles from the model grid.

- Chamberlain and Stucchi (2007) propose that waste feed particles are dealt with separately and given erosion thresholds in line with those measured by Sutherland et al. (2006).

- **They also found that the uncertainty in the proportion of waste feed accounted for most of the uncertainty in model predictions**

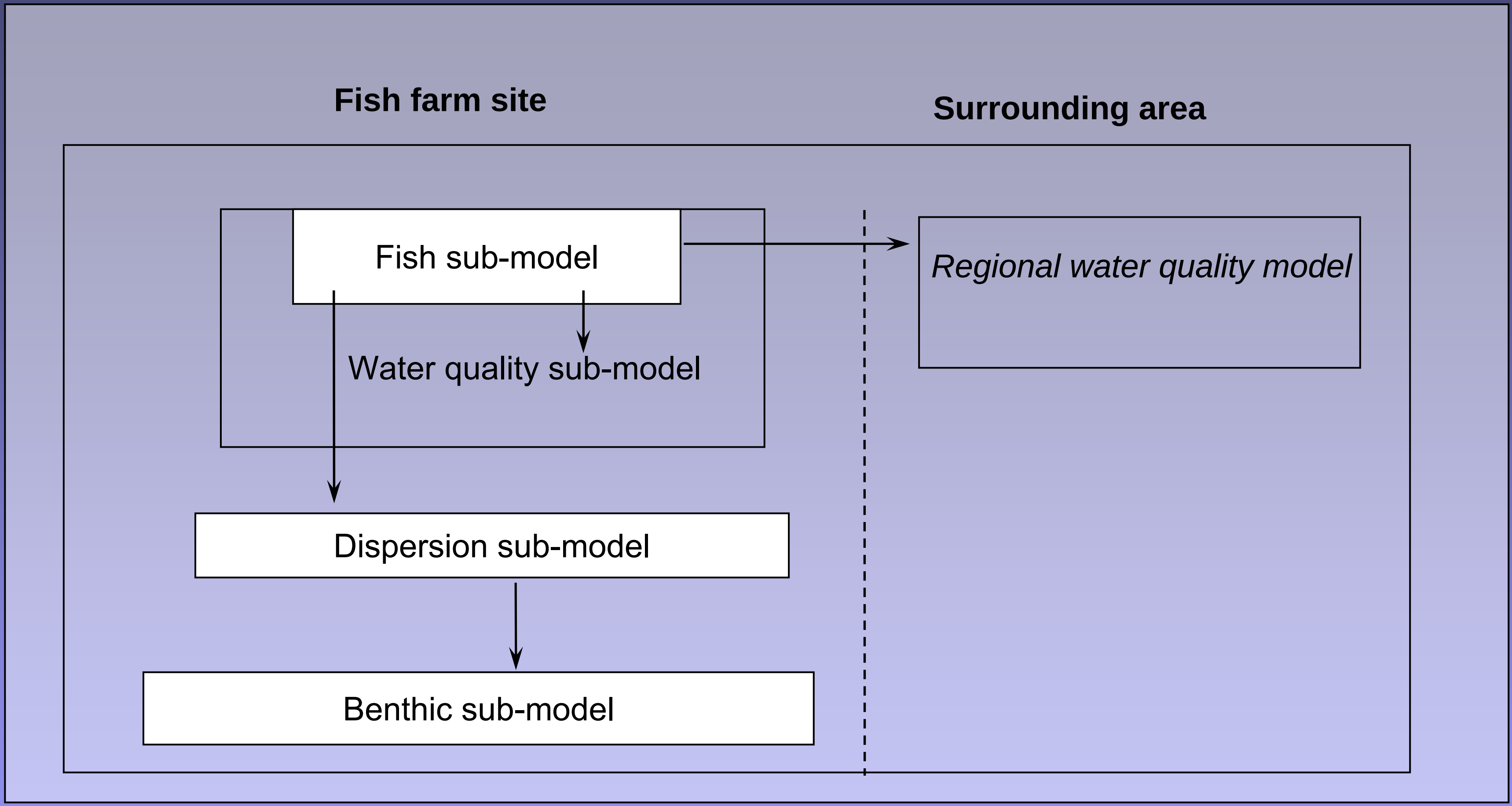
MOM Norway

- MOM (Modelling – Ongrowing fish farms - Monitoring) (Ervik *et al.*, 1997).

- In the MOM system the environmental objective for the management of fish farm sites is that their impact must not exceed threshold levels that safeguard the wellbeing of both the fish and the environment.

- The aim of the model is to estimate the maximum production of fish that can be allowed without exceeding the holding capacity at the site (Stigebrandt *et al.*, 2004).

- The model comprises four sub-models (a fish model, a water quality model, a dispersion model and a benthic model) and is linked to a previously developed model on environmental quality in fjords (Stigebrandt, 2001). The model was developed so it can be utilised by both environmental administrators and fish farmers.



- **MOM** The local site model is linked to a regional (inshore) water quality model (Fjord Environment) (Aure & Stigebrandt, 1990). The output parameters from the fish sub-model are used as input parameters to the water quality sub-model, the dispersion sub-model and the regional water quality model. The dispersion sub-model delivers input parameters to the benthic sub-model. Check ECASA website

- There have been several other approaches to modelling wastes from salmon culture including the modular approach of Silvert and co-workers (Silvert & Cromey, 2001; Silvert & Sowles, 1996) and the GIS framework developed by Ross and Telfer and co-workers (Corner et al., 2006; Hunter, Telfer & Ross, 2006; Perez et al., 2002) but these are not currently used in regulation.

6 Regulation and mitigation of sediment impacts

- The objectives of regulation can be separated into three areas:
  - protection of legitimate users of the environment, such as tourists or fishermen, so that environmental resources are fairly distributed.
  - protection of the environment for its biological structure including protection of important/rare habitats and species
  - protection of ecosystem functions such as the recycling of nutrients and the maintenance of oxygen levels
- The first of these, which is the subject of Integrated Coastal Zone Management is addressed in the next section.

Protecting structure

- Interactions between aquaculture and sensitive habitats or species can be minimised by establishing aquaculture zones in areas with less sensitive/important/rare habitats, or by designations that more closely regulate developments with respect to their interactions with particular features of concern.

- In Europe, Special Areas of Conservation (SACs) have been established under the Habitats Directive (92/43/EEC) for the protection of specific habitats.

Ecosystem function

- Regarding the third objective, maintaining ecosystem function, regulation has been developed in all salmon growing countries to preserve the capacity of sediments to efficiently recycle organic wastes.
- Regulators have generally set sediment quality standards to protect the benthic environment around farms from severe degradation.

Indicators

- All salmon regulators have established Sediment Quality Criteria (SQC) or equivalents as indicators of when they will take action in order to reduce impacts e.g. by reducing the maximum allowable biomass or by entirely revoking the discharge consent.
- Many benthic indicators co-vary to some extent and together the SQC clearly show what regulators consider to be unacceptable benthic conditions.

Monitoring

- In general, fish farming licences have monitoring conditions specified in detail: both their level (i.e. the number of stations, types of measurement and analysis) and their frequency are matched to the perceived risk of the farm.
- For example, a small farm over a hard substratum with strong currents will be monitored less intensively than a large farm over a soft substratum with weak currents.
- For Scotland, this process is given in great detail, together with its underlying philosophy and science, in the regularly updated Fish Farm Manual that can be downloaded from the SEPA website

  (www.sepa.org.uk).

Animals are seen to matter

- SQCs are set to prevent azooia: for example, in Scotland, at least 2 species at high abundance are required as a mean across all replicates grabs, and not more than one replicate grab sample should contain no macrofaunal animals.

- It is well established, although the process is not well understood (section 2), that the presence of macrofaunal animals increase the rate of degradation of organic carbon (Heilskov & Holmer, 2001). Thus, the objective is that farm sediments should contain a high abundance and biomass of bioturbating macrofaunal animals to enhance carbon degradation.

- This is in accordance with the objectives for Norwegian fish farming and the monitoring programme in use (NSA, 2000) and is also consistent with the approach taken in other salmon farming countries (Wilson, Magill & Black, In press).

- The SQC are levels at which the regulator in Scotland may take action against the farmer.

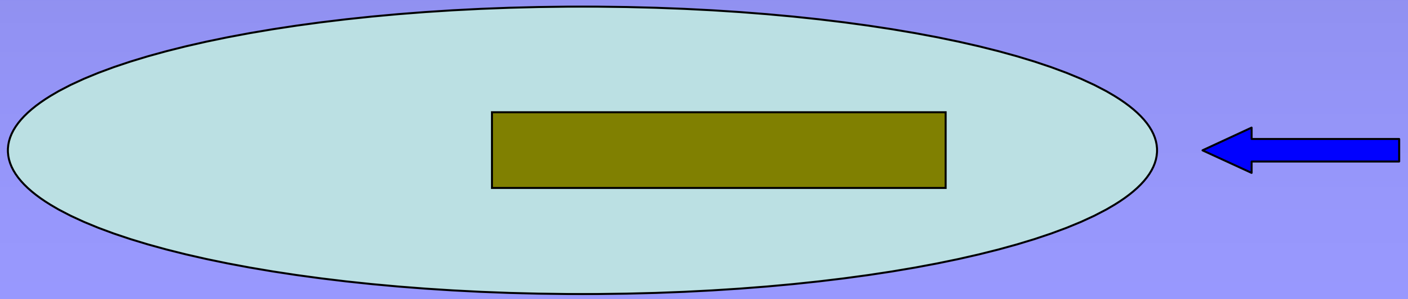
- Implicit within the approach are:
  – that the farmer is required to monitor the sediments around the farm to measure compliance or otherwise, and that this monitoring may be independently audited, and
  – the concept of the Allowable Zone of Effects (AZE) or mixing zone.

AZE

- The AZE or mixing zone concept is used in many salmon farming countries. The AZE represents an area around the farm where some deterioration is expected and permitted.

- Thus for several determinands, two SQCs are proposed: one within the AZE and one at any point outside the AZE. The SQC inside the AZE is less demanding than that outside the AZE.

- The SQC approach thus constrains the level of ecological change while the AZE limits the spatial extent of major changes.



- In Scotland, the AZE was formerly defined as the area bounded by a line 25m from the cage array perimeter

- Now the AZE is determined with reference to the dispersiveness of the site using a modelling approach giving site-specific AZEs.

- This allows larger AZEs, and therefore larger discharge consents, in areas of high dispersion and is driven by the policy goal of encouraging development in more dynamic environments and reducing reliance on sheltered fjordic sites with low currents and, generally, longer residence times.

SEPA SQC

Determinand	Action Level Within AZE	Action Level Outside AZE
Number of taxa	Less than 2 polychaete taxa present (replicates bulked)	Must be at least 50% of reference station value
Number of taxa	Two or more replicates with no taxa present	
Abundance	Organic enrichment polychaetes present in abnormally low densities	Organic enrichment polychaetes must not exceed 200% of reference station value
Shannon - Weiner Diversity	N/A	Must be at least 60 % of reference station value
Infaunal Trophic Index (ITI)	N / A	Must be at least 50% of reference station value
Beggiatoa	N/A	Mats present
Feed Pellets	Accumulations of pellets	Pellets present

Determinand	Action Level Within AZE	Action Level Outside AZE
Teflubenzuron	10.0 mg/kg dry wt/5cm core applied as a average in the AZE	2.0 µg/kg dry wt/5 cm core
Copper	*Probable Effects* 270 mg/kg dry sediment *Possible Effects* 108 mg/kg dry sediment	34 mg/kg dry sediment
Zinc	*Probable Effects* 410 mg/kg dry sediment *Possible Effects* 270 mg/kg dry sediment	150 mg/kg dry sediment
Free Sulphide	4800 mg kg-1 (dry wt)	3200 mg kg-1 (dry wt)
Organic Carbon	9%	
Redox potential	Values lower than -150 mV (as a depth average profile) OR Values lower than -125 mV (in surface sediments 0-3 cm)	
Loss on Ignition	27%	


6
9

Norway - standards

- At the fish farm site a number of indicators are used to determine how much the sediment is impacted by the farm activity. Because the survey is repeated regularly, at intervals determined by the extent of the environmental impact, trends in the environmental impact can be followed closely.

- At least ten grab samples are collected at the site and both the average condition at the site and the conditions under different parts of the fish farm are revealed.

- Three groups of sediment parameters are used:
  - 1) presence or absence of animals larger than 1 mm in the sediment,
  - 2) pH and redox potential and
  - 3) qualitative determination of outgassing, smell, consistency, colour of the sediment, grab volume and thickness of the layer of deposits.

- All parameters are assigned points, according to the extent to which the sediment is affected by organic material. The points are added and the higher the sum the more affected the sediment. Since many parameters are used in concert the survey is less sensitive to anomalies in individual parameters.

- EQS have been established which divide the sediment condition into four categories equivalent to the four degrees of exploitation and like the Scottish system there are upper threshold limits for allowable effects.

Norway vs Scotland

- Most countries (Wilson et al., In press) follow some variant of the approach in Scotland where benthic monitoring is comprehensive, covering a wide range of determinants including a full macrofaunal survey at several stations, usually once every 2 years at the predicted maximum biomass.

- This is in contrast to the Norwegian MOM system where higher frequency but less extensive investigations are required and full macrofaunal surveys are less common and mainly used outside the AZE.

Assimilative Capacity

- The benthic assimilative capacity is usefully defined as the maximum rate of input such that benthic communities do not deteriorate beyond minimum criteria even on continuous usage.

- Salmon are farmed on a 2 year cycle where maximum biomass is achieved and sustained throughout the second farming year.

- Thereafter, farms are usually cleared for 6-8 weeks before the farming cycle is restarted.

- Thus every second year the seabed under the cages experiences a high sedimentation rate and every other year starts with a period of no organic input followed by a steady rise to maximal levels as the fish grow.

Fallowing

- Fallowing is a term often used for 2 distinct processes:
  - the period of a few weeks between farming cycles when fish are absent from a site after harvesting and before the next restocking – primarily to break disease cycles; and
  - the practice of site rotation where a site may be left empty for one or more years for the sediments to recover.
- Site rotation has been recommended both by regulators and by scientists (e.g.,Carroll *et al.*, 2003) as a method of reducing benthic impacts by allowing time for recovery.

- However, there is evidence that such site rotation merely allows an otherwise unsustainable site to remain in production on a periodic basis (Hall-Spencer et al., 2006; e.g., Pereira et al., 2004).

- A better solution would be to limit the scale of production at any site such that it does not break EQS’s even after repeated farming cycles i.e. within the assimilative capacity of the site.

- However, this may not be a practical option for other reasons, e.g. lack of alternative sites at an appropriate distance from logistical support.

7 Salmon farming and other users of the coastal resource

Principles of ICZM:

1. A Broad "Holistic" Perspective (Thematic and Geographic)

2. A Long Term Perspective

3. Adaptive Management during a Gradual Process

4. Reflect Local Specificity

5. Work with Natural Processes

6. Participatory Planning

7. Support & Involvement of all Relevant Administrative Bodies

8. Use of a Combination of Instruments

Locational Guidelines

In Scotland the Locational guidelines have designate the whole coastline on the basis of nutrient enhancement and benthic effects:

Category 1: where the development of new or the expansion of existing marine fish farms will only be acceptable in exceptional circumstances.

Category 2: Where new development or expansion of existing sites would not result in the area being re-categorised as category.

Category 3: where there appear to be better prospects of satisfying nutrient loading and benthic impact requirements, although the detailed circumstances will always need to be examined carefully.

Locational Guidelines for the Authorisation of Marine Fish Farms in Scottish Waters (2005)

Multiple stressors

- Relatively few studies have considered cumulative and synergic impacts of multiple activities (salmon farms, agriculture, shellfish farms, water treatment works, industrial effluents) in shared water sheds and water bodies (Strain, Wildish & Yeats, 1995).
- Nutrient and oxygen budgets are likely most important environmental element.
- In terms of benthic impact, one of the major anthropogenic impacts in the marine environment comes from dredging or benthic trawling (Kaiser *et al.*, 2006) with recent evidence that impacts are long lived and change ecosystem functioning (Tillin *et al.*, 2006) over wide spatial scales (Hiddink, Jennings & Kaiser, 2006).
- In contrast, while space utilisation in a particular bay might be high, salmon farms occupy only a tiny fraction of coastal seas.

- By designating areas for aquaculture, or giving farmers exclusive access to sites, it is likely that farms may act as refuges for some species.

- This is especially obvious with sea bass/bream farming in the Mediterranean, where wild fish aggregate around farms and may experience reduced fishing pressure (Dempster et al., 2005; Dempster et al., 2004).

- It is thus vital to ensure that commercial fishing is not allowed close to fish farms as this might have the effect of increasing catch per unit effort if target species aggregate there.

Oxygen demand

- Regarding the benthos, some attention has been given to the potential for particulates from fish farms to cause hypoxia in fjordic basins including a component of the FjordEnv component of the Norwegian MOM system (Stigebrandt, 2001) and a recent study in Scotland (Gillibrand *et al.*, 2006).

- The latter modelling study concluded that pelagic oxygen demand was more important than benthic oxygen demand in terms of depleting oxygen and in most loch systems this meant that particulate carbon from the farm had little effect on the overall oxygen depletion rate of isolated bottom waters.

- However, this report acknowledged that understanding in this area is weak as few measurements of benthic and pelagic oxygen demand have been made in such systems.

- In many areas hyperntrification of the water column rather than loss of benthos is likely to be a much more important constraint on industry expansion in semi-enclosed water bodies, but in some fjords the water exchange in the upper layers can be high yet the bottom water stagnant and the deposit of organic fish farm waste directly to the deep area could result in hypoxia.

Marne Spatial Planning

- Marine spatial planning, an element of ICZM, is on the policy agenda for most developed maritime countries (Boyes et al., 2007; Bruce & Eliot, 2006; Cicin-Sain & Belfiore, 2005; Doherty & Butler, 2006; Douvere et al., 2007).
- Some studies have used GIS tools to determine areas with the appropriate environment for farming while also minimising potential conflicts with other users (Hunter et al., 2006; Perez, Telfer & Ross, 2003).
- Recently there has been an examination of truly offshore aquaculture technologies (Colbourne, 2005; Plew *et al.*, 2005) and socio-economics (Skladany, Clausen & Belton, 2007) in the anticipation that such installations will have fewer environmental impacts and be capable of operating at much greater scales.
- However, a recent report from the UK (James & Slaski, 2006) highlighted “deficiencies in technical capacity, biological understanding and legal impediments that may stifle attempts to conduct aquaculture offshore”.

- A variety of regulatory tools exist to prevent aquaculture expansion in areas that are considered environmental sensitive or important (section 7). Some of these are directly focussed on aquaculture (e.g. Gillibrand *et al.*, 2002) whereas some, such as European Special Areas of Conservation, require an assessment of any human development with respect to the feature that has prompted the designation.

- There is often an imperfect knowledge of the diversity of benthic species and habitats in the coastal zone, so the designation of a percentage of the coastal area for conservation purposes (Marine Protected Areas) should be encouraged without the need to specify any the particular conservation feature.

- Such MPAs should provide protection from a wide range of human activities, including intensive aquaculture, and should ideally form part of a planned network (Gell & Roberts, 2003; Roberts et al., 2003; Roberts, Hawkins & Gell, 2005a; Rodwell & Roberts, 2004).

8 Site selection and commercial considerations

- A key commercial constraint is the availability of good sites as in most countries the availability of new sites is strictly limited.
- In general, a good fish farm site has:
  - moderately strong currents (means of 5-10 cms^{-1}),
  - is moderately deep (40+ m),
  - has low exposure to large waves (significant wave heights of 2 m or less),
  - is out of sight of tourist facilities and distant from major human habitation,
  - is sufficiently far from other salmon farms as to reduce disease transmission between farms (ideally greater than one tidal excursion distance), and
  - is not in an area of important natural or social heritage.

- Additionally, sites should not contribute additional nutrients to the water body that would exceed the assimilative capacity taking other sources into account.

- There are several modelling tools available to farmers and regulators to help optimum site selection

- The site should have access to sufficient medicine discharge permission to reduce the risk of cross-infection between farmed and wild salmonids, and should not be within the immediate vicinity of a river with an important salmon river.

- No clear advice is possible on this last topic as escaped farmed salmon have been shown to be capable of travelling long distances before entering rivers.

- In recognition of this, and of the potential damage to wild salmon populations from escapes, farmers are involved in mitigation schemes which focus on appropriate engineering (e.g. NYTEK in Norway) and escape recovery plans.

- A site with the above characteristics should reduce the risk of significant environmental damage allowing the farmer to operate at a scale that allows economic production in a highly competitive market.

- There are of course additional commercial considerations: the site must be convenient to human infrastructure such as labour, accommodation, transport facilities, and ideally markets.

- Operator safety is also a key issue especially where more exposed sites are considered.

- Aquaculture bodies are already interested in assessing their carbon footprint throughout the production cycle and this interest is likely to grow in the coming years as climate change concerns increase along with fuel prices.

In-feed medicines

- As the industry moves to larger cages and more exposed environments, the logistics of bath-treatments become increasingly difficult. Thus the industry must rely on in-feed medicines for the future.
- The in-feed medicine Slice (emamectin benzoate) has a good record in terms of toxicity to benthic invertebrates (Telfer *et al.*, 2006) but there is anecdotal evidence that lice are becoming resistant to this product.
- Should resistance continue to grow, as seems inevitable, and no benign but efficacious successors become available, the prospect of either increased lice burdens or in-feed products with higher ecotoxicity is a serious cause for concern.

Conclusions and recommendations for further research

- Scientific uncertainties still exist which do not allow us to confidently predict many important benthic responses, e.g. the precise determination of the accumulation rate that causes azoia.

- For this, we require much better understanding of the relationships between organic accumulation, sediment geochemical response, consequences for the faunal community, and the role of bioturbation and bioirrigation in carbon degradation by microbial processes.

- This requires a combined experimental, observational and modelling approach, with a focus on sediment biogeochemistry.
- Ideally, such understanding would lead to simple chemical proxies (indicators) of sediment state from which faunal community state could be inferred.
- However, as recovery processes have a biological dependency (e.g. seasonal larval supply) it is also important that we increase our understanding of invertebrate life histories at the species level – a grossly under-researched area.
- Much better information on the rates of wastage and faecal output is required.
- Further work on resuspension is necessary.

The future for the salmon industry must include:

- continuously improving environmental performance;
- reduced waste feeds, e.g. through more use of feedback-controlled feeding;
- better matches between benthic assimilative capacity and site biomass;
- common environmental quality objectives across salmon growing countries with appropriate quality standards set to offer a similar levels of environmental protection;
- and high standards of monitoring and enforcement by well resourced regulatory bodies.

These objectives can be best met by:

- co-operation between farmers, regulators and scientists, including co-funding of research (e.g. SARF in the UK);
- industry funding of monitoring; state funding of environmental auditing;
- increased transparency of environmental information;
- improved communication between regulators in different countries;
- appropriate training for both farmers and regulators;
- and improved scientific understanding and its application through effective regulatory tools, models and indicators.

Chile

- The rapid increase in the Chilean salmon industry has not been matched by published scientific studies on benthic impacts.

- A robust programme of scientific research on benthic impacts in Chile should be implemented to underpin regulatory efforts to protect the environment.

- Regulatory capacity for environmental auditing and enforcement must be enhanced

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