Not to be cited without prior reference to the authors C.M. 1993/F:19

THE EFFECT OF HARROWING AND FALLOWING ON SEDIMENT QUALITY UNDER A SALMON FARM ON THE WEST COAST OF IRELAND

by

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ABSTRACT.

It has been well established that the major area of impact on the marine environment from organic wastes produced by fish farms is the sea floor directly underneath and at some distance away from the cages. It has been suggested that this build-up of wastes can be detrimental to fish health due to the release of toxic gases and is a possible source of pathogens. In order to overcome these effects, harrowing or raking the sediments to release gases, disperse organic material and speed up the return of more normal sediment quality conditions has been advocated.

This paper presents findings from a survey designed to describe pre- and post-harrowing sediment conditions following a fallowing period under a salmon farm off the west coast of Ireland. Variables such as depth of the redox layer and types and numbers of benthic animals were used to describe the conditions which pertained both before and after the harrowing took place. A diver-operated Sediment Profile Camera was also used to document sedimentary conditions and standard underwater photographic methods described the sediment surface in general.

Results show that before the harrowing took place, the various measures of sediment quality described a heavily impacted sea floor with low redox levels on the sediment surface, high organic carbon values in the sediment and a very poorly developed infauna. Diving observations and underwater photography showed that the surface was dominated by mats of *Beggiatoa* sp. and that the sediment surface was blackened and mounded with waste food. A post-harrowing survey carried out three months after the event, demonstrates that conditions had significantly improved with high redox levels being recorded up to two centimeters into the sediment, low sedimentary organic carbon values and a well developed, if reduced, infauna. The paper discusses the benefits of harrowing and fallowing and how, by significantly enhancing sediment quality, production success and environmental quality can be ultimately improved.

INTRODUCTION

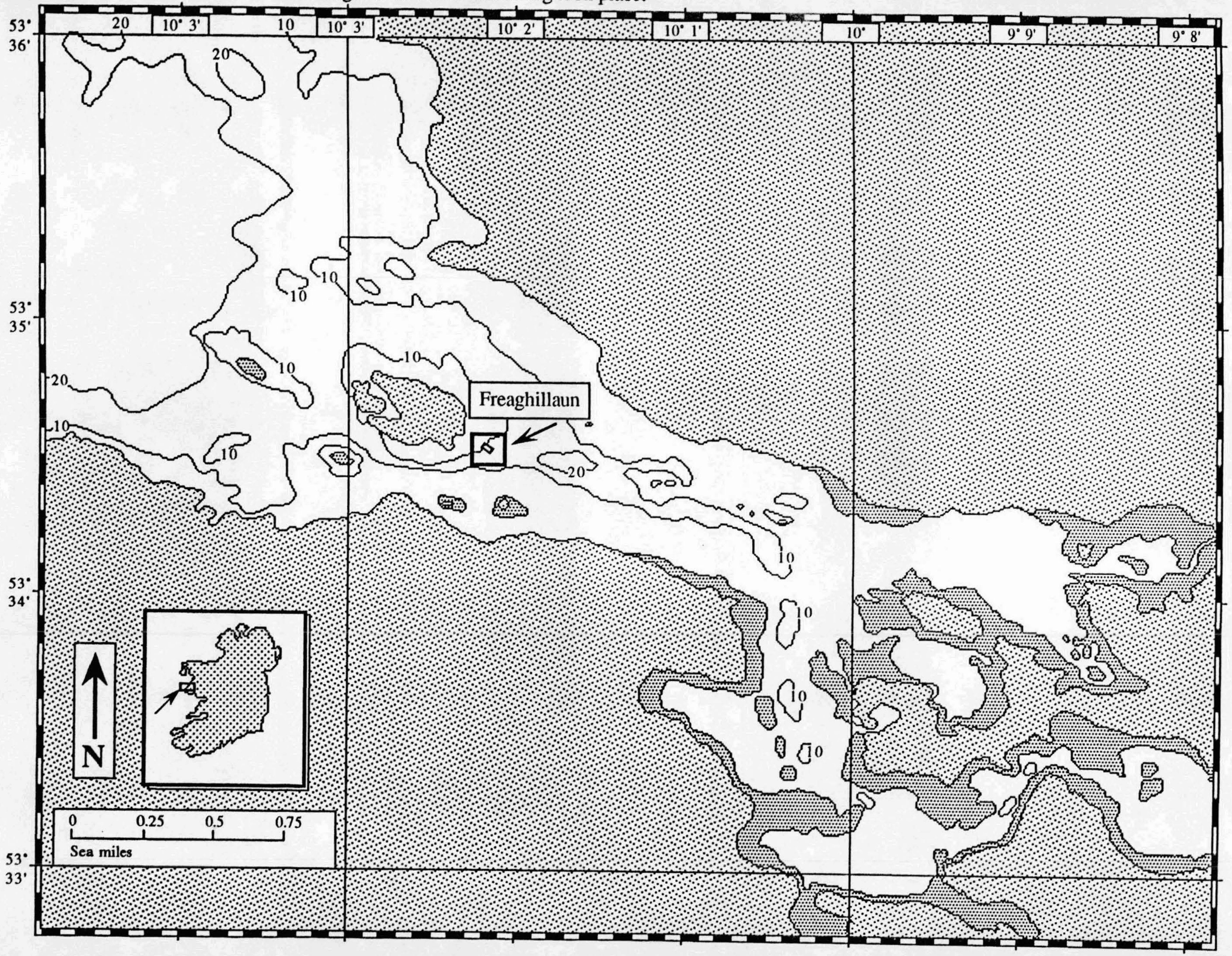
Tully Mountain Salmon Farms have been producing salmon for the national and international markets from two locations in Ballynakill Harbour, Co. Galway since the mid 1980's. A report to Tully Mountain Salmon Farms by Aqua-Fact International in August 1991 (Aqua-Fact International, 1991) showed that conditions under and in the vicinty of one set of their cages at Freaghillaun were impacted due to organic enrichment which could have led to conditions deleterious to fish health. As part of a site management programme to maintain high quality undercage seafloor conditions, Tully Mountain Salmon Farms carried out an extensive sediment reworking programme in the vicinity of their Turmec cage system, east of Freaghillaun, Ballynakill Harbour (Figure 1). This particular location has been used to produce approximately 200 tonnes of salmon annually.

Organic enrichment commonly results from intensive mariculture in inshore waters (Gowen *et al.,* 1988). Uneaten food and faeces settle to the bottom and breakdown of this detritus can contribute to low oxygen conditions in the overlying water column. In addition, potentially toxic decay products such as methane and hydrogen sulphide can outgas into the water from the bottom. These conditions may cause physiological stress, disease, reduced growth, or death of cultured species suspended over such an enriched bottom.

Studies of organic enrichment from a variety of sources (sewage outfalls, wood pulp effluent, disposal of dredged sediment and mariculture systems) generally show three common stages of environmental response:

1) Immediately following initial enrichment (starting with natural conditions), natural plant and animal production commonly increase. This is the early "Productivity Enhancement" Stage of organic enrichment.

Figure 1. Location of the site at Freaghillaun where narrowing took place.



2) The Enhancement Stage is terminated if organic loading continues and exceeds the capacity of the systems to efficiently recycle organic matter. Organic matter then accumulates on the bottom. Decay processes increase the oxygen demand of the sediment and hydrogen sulphide accumulates in the sediment. This is the "Early Stage of Overloading".

3) As organic matter continues to accumulate, oxygen may be depleted in bottom water. Hydrogen sulphide and methane can then outgas from the sea floor and enter the water column. This is termed the "Degradation" Stage. The "Degradation" Stage can be long-lasting and compromise the subsequent use of an embayment for many kinds of commercial and sport fisheries.

Intensive mariculture can lead to the three stages of enrichment described above. Unconsumed food pellets and faeces are sources of organic detritus that settle to the bottom either directly under, or at some distance from, the cages and cause the on-set of hypoxic condition leading to the outgassing of methane and the development of sulphur-reducing bacterial colonies such as *Beggiatoa* sp. on the seafloor.

Figure 2 shows the sequence of potential habitat degradation starting with a natural condition (without rafts or cages). The figure legend describes the effects of local organic loading on sediment and water chemistry and seafloor biota. A more detailed view of the Degradation Stage is shown and described in Figure 3. Oxidative decay of pellet and faecal detritus results in a reduced supply of oxygen in sediment pore waters. Anaerobic (without oxygen) reactions then take-over, releasing hydrogen sulphide and methane gas. These potentially toxic gases are liberated into the overlying water column. In turn, near-bottom oxygen is used-up in the decay of organic matter and oxidation of reduced compounds such as methane, hydrogen sulphide and ammonia.

The above chemical changes dramatically affect the resident seafloor biota. While this would appear to be of little immediate consequence to a mariculture system located several meters above the bottom, the seafloor biota play a major role in "processing" and recycling of organic detritus from such a cage or raft. This "processing" involves the direct consumption of organic detritus, the oxygenation of sediments at depth by the activity of the animals and physical stirring of the upper few centimeters of the bottom (a process called bioturbation). This stirring process is important for breaking down and recycling organic matter. Bioturbation is a key process for determining the capacity of the seafloor to decompose and recycle organic matter.

Figure 2.The effect of intensive cage mariculture on benthic processes (4 Stages).

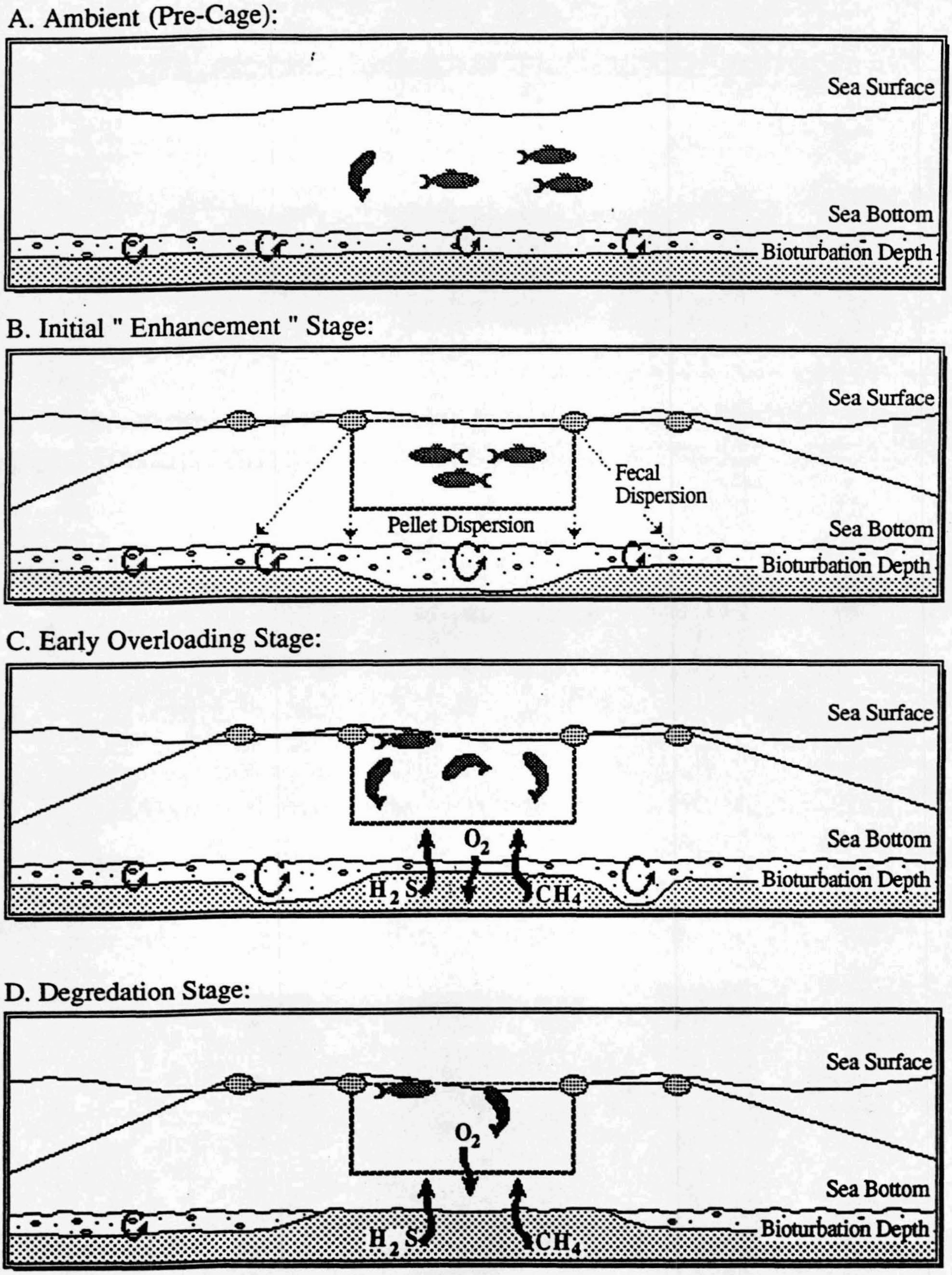
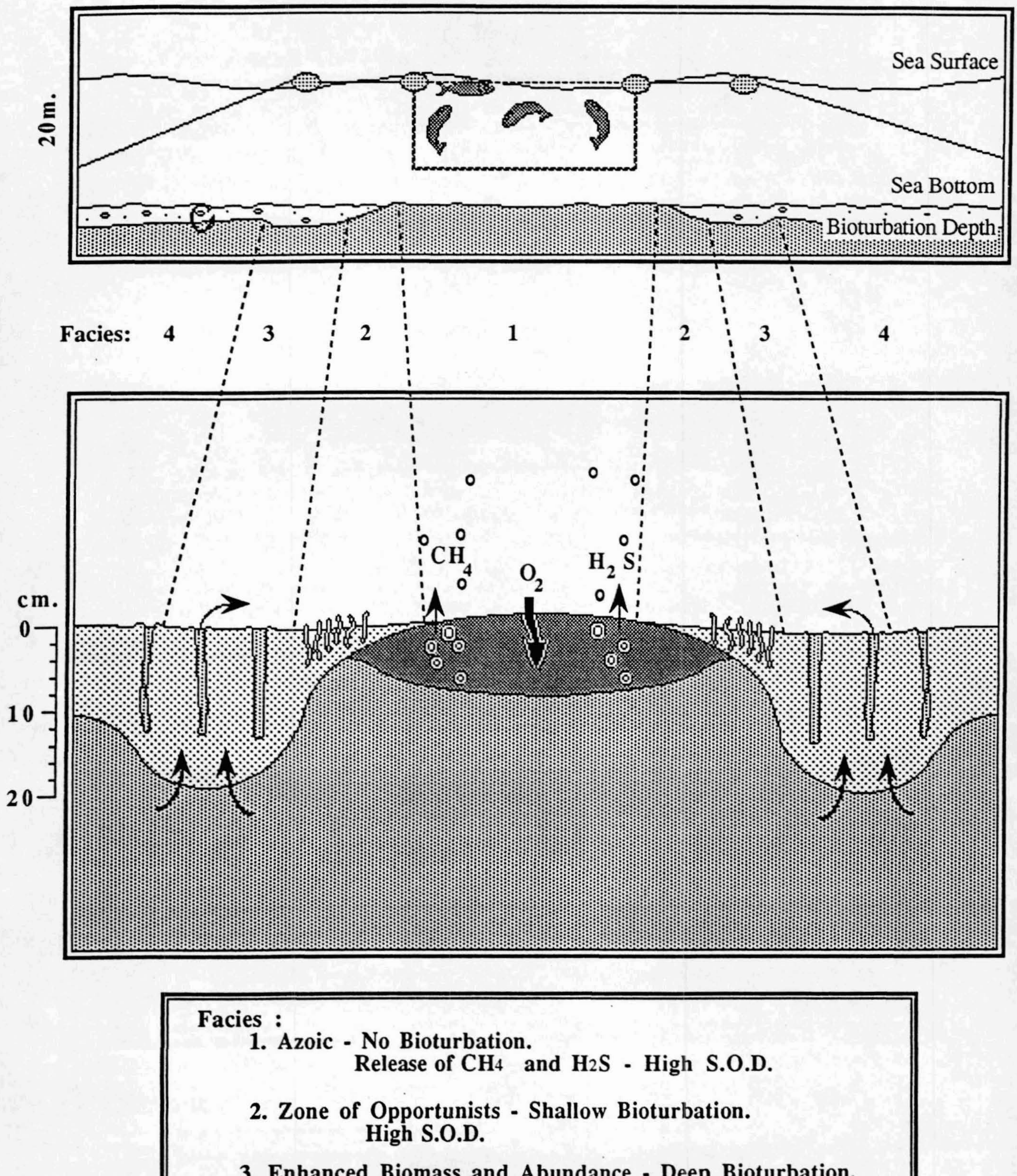


Figure 3. A detailed view of the degradation stage.



Facies :

1. **Azoic - No Bioturbation.**
   Release of CH_4 and H_2S - High S.O.D.
2. **Zone of Opportunists - Shallow Bioturbation.**
   High S.O.D.
3. **Enhanced Biomass and Abundance - Deep Bioturbation.**
   Lower S.O.D.
4. **Ambient Biomass and Abundances - Moderate Bioturbation.**
   Low S.O.D.

The bioturbation process only works efficiently in the early stages of organic loading (Ambient or Enhancement Stages of Figure 2). Loading rates of kilogram quantities of reactive carbon per square meter per year can cause the local extinction of important bioturbating species and terminate the mixing process. Once bioturbation has stopped, the Degradation Stage is rapidly reached with severe consequences for the whole system.

The importance of physical stirring for digestion of organic matter is well understood by sanitary engineers who design treatment plants. Physical stirring and aeration of sewage sludge is done in these plants to stimulate bacterial digestion of sewage. In the case of mollusc cultivation areas, shellfish beds are periodically either raked, harrowed or worked over with a water jet system to remove excessive silt from the beds (Kinne, 1977; Rask, 1988; Heral, 1990) in order to maintain the beds in optimum condition. In agricultural systems it has long been realised that ploughing enhances productivity and maintains that part of the ecosystem in a relatively high level of productivity. O'Connor *et al.* (1991) suggested that harrowing maybe a useful management option in the case of marine finfish locations when the farmer is faced with the deterioration of benthic conditions under the cages.

Tully Mountain Salmon Farm undertook this experimental sediment harrowing programme in order to have a better understanding of the effects of such work. In particular, the harrowing was carried out to breakdown existing redox conditions by facilitating sediment-oxygen uptake, to breakup and disperse *Beggiatoa* spp mats, to release sediment-bound gases such as methane and to spread out and disperse organic matter in the form of uneaten food and faeces.

MATERIALS AND METHODS

The surveys of conditions under and around the cages at Freaghillaun were based on dive studies which included sediment surface photography and cores for sediment biology and chemistry.

Benthic survey

The pre- and post-harrow benthic surveys as described by O'Connor *et al.* (1991), comprised of a photographic survey with additional diver-made observations over the area in general, Sediment Profile Imagery and cores for macrofaunal and chemical analyses. The pre-harrow study was carried out in December 1991 and the post-harrow survey in April, 1992. Diver observations included :

a) signs of out-gassing from the sediment,

b) evidence of oxygen-depleted conditions such as the presence of sulphur-reducing bacteria (*Beggiatoa* sp.) and /or the presence of anaerobic, reducing sediments,

c) evidence of mounding of waste material,

d) an assessment of the general appearance of the sediment, and

e) evidence of mobile and sessile macrofaunal activities.

For a full description of SPI, please see O'Connor *at al.,* 1989.

Figure 4 shows the route of the photographic dive transect and the locations where the Sediment Profile Imagery Camera was used and cores were taken. A Nikonos 5 camera fitted with a 15 mm lens and flash was used to photograph surface conditions under the cages.

Cores (20 cm deep, 8 cm internal diameter) were used to collect faunal samples. Two samples taken to depth of 10 cm were collected at each location. Due to the commercial nature of the work, it was not possible to reserve portion of the under cage environment as a control location. The material collected in these cores was washed through a 1.00 mm sieve prior to fixing in 4% buffered formaline and later preservation in 70% alcohol. On return to the laboratory, the samples were sorted under a microscope (x 10 magnification). All faunal returns were identified to species level where possible. Faunal nomenclature follows Howsen (1987) and identification was according to standard texts and keys.

Harrowing

Harrowing at the Freaghillaun site began on 23rd January, 1992 and continued for the following four days. Harrowing began at high water to ensure that any sediment brought into suspension was carried out of the bay and away from local mollusc producing areas. The harrow, consisting of a 15 m long metal bar to which were welded 50 20 cm long and 5 cm wide teeth, was towed backwards and forwards under the cages.

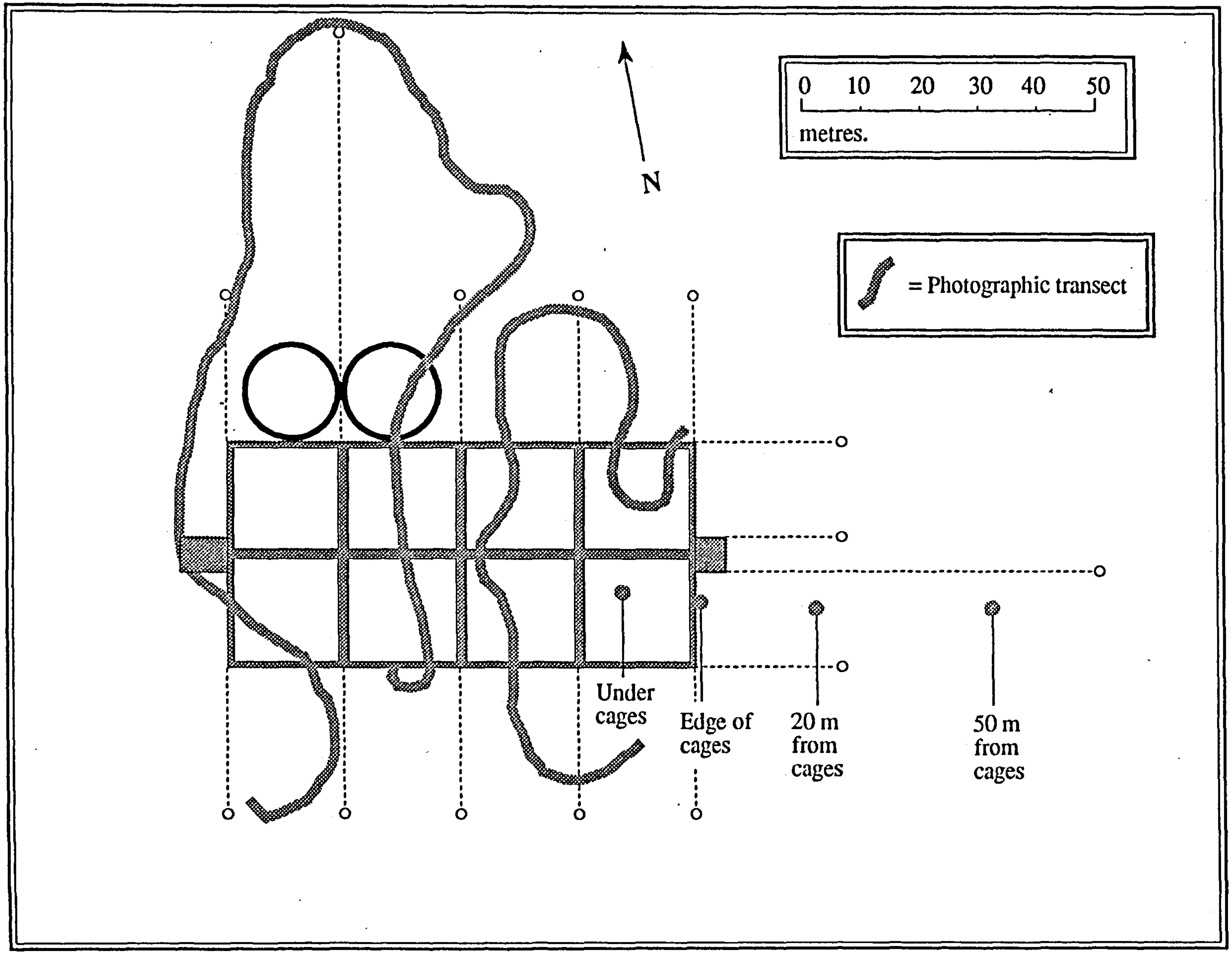


Figure 4. Faunal core locations, Sediment Profile Imagery (SPI) stations and photographic pre- and post-harrow transects at Freaghillaun.

RESULTS

Surface Sediment Photography
Pre-Harrow Survey

The bottom type underneath and in the vicinity of the cages consisted of a soft muddy sand which lies over a basement layer of relict *Turritella* shells. For the most part, the surface of the sediment was brown in colour indicating oxygenation of at least the superficial sediment layer. However, in places the sediment surface was gelatinous in texture and had a black colour indicating some accumulation of organic-rich material. This was further substantiated from core sampling underneath and at the edge of the cages which revealed that, apart from a superficial surface layer, the sediments were hypoxic (i.e. lacking in oxygen), black in colour and with a strong smell of hydrogen sulphide. In fact, sediments taken from the site at a distance of 50 m from the cages were also anoxic and black in colour and this condition was apparent close to the surface of the sediment.

There was a light covering of *Begiattoa* sp. underneath the cages and this changed to a patchy distribution on moving away from the cages up to a distance of c. 30 m.

There was some mounding of uneaten food underneath the cages indicating an accumulation of waste material but this was not extensive or excessive. Outgassing of methane was prevalent in those areas showing mounding of wastes.

The obvious surface fauna underneath the cages was not particularly rich or abundant. The common and spiny starfish *Asterias rubens* and *Marthasterias glacialis* , respectively) and swimming and green crabs (*Liocarcinus depurator* and *Carcinus maenas*, had a general low level of occurrence. The sea slug, *Philine aperta*, was also noted underneath the cages. Pollack and /or coalfish were observed feeding on food particles underneath the cages. One specimen of the scallop, *Pecten maximus* , and occasional individuals of the plumose anemone, *Metridium senile*, attached to suitable hard substrates, were also observed.

Once beyond 20 to 25 m of the cages, the surface fauna was rich with particularly dense populations of the sea slug, *Philine aperta* . Burrowing cerianthid anemones were also common while the hydroids , *Nemertesia antennina*, *Tubularia indivisa* and *Obelia* sp. were observed attached to protruding rocks. Pipefish, dragonets and blennies were also seen. Casts of grey sediment,which show the visible effects of the presence of an active bioturbating infauna are probably formed by the lug worm, *Arenicola.*

Post-Harrow Survey

Photographs of the sediment surface under and around the cages showed a diverse and varied macrofauna consisting of species such as the sea pen *Virgularia mirabilis,* the lugworm, *Arenicola* and surface dwelling species such as paddle worms (Phyllodocidae), tectibranchs (*Philine* sp.), gastropods (*Turritella communis*), hermit crabs, *Eupagurus,* and velvet crabs, *Leiocarcinus* and starfishes *Asterias rubens* and *Marthasterias glacialis.* Only a small amount of *Beggiatoa* was seen under the southwest corner of the cage system.

There were no signs of out-gassing from the sea floor. The colour of the sediments under and around the cages was brown indicating oxygenated conditions and a normal amount of organic matter.

Core sampling

Fauna

Pre-harrowing survey

Table 1 lists the species recorded from the cores taken along the transect at four locations away from the cages. In all only 8 species were recorded of which 5 are polychaetes, 2 are bivalves and one an opisthobranch. As can be seen from Table 1 densities of all species were very low.

Species	Under	Edge	20 m	50 m
Anaitides maculata				1
Ophryotrocha puerilis				6
Malacoceros fuligenosus	8		2	
Capitella capitata			1	
Melinna palmata		1		
Philine aperta				6
Mytilus edulis	1			
Lucinoma borealis			1	

Table 1. Macrofaunal species identified from pre-harrowing diver-taken cores, Freaghillaun Turmec cages.

Under-cage	A	B
Nematoda	+	+
Anaitides mucosa	26	23
Lumbrineris gracilis	1	1
Malacoceros fuligenosus	26	29
Capitella capitata	216	249
Arenicola marina	1	-
Abra alba	2	4
Diastylis laevis	1	-

Edge	A	B
Nematoda	+	+
Anaitides mucosa	15	29
Eteone flava	-	2
Glycera tridactyla	-	1
Lumbrineris gracilis	-	2
Malacoceros fuligenosus	17	14
Capitella capitata	136	94
Mytilus edulis	-	1
Abra alba	15	10
Microprotopus maculatus	1	-
Ampelisca tenuicornis	-	3
Urothoe elegans	-	1

20 m	A	B
Nematoda	+	+
Oligochaeta	+	+
Harmothoe sp	1	+
Anaitides mucosa	2	2
Glycera tridactyla	1	1
Nephtys hombergii	-	1
Notomastus latericeus	4	1
Abra alba	7	10
Ampelisca tenuicornis	3	8
Eudorella truncatula	-	1

50 m	A	B
Nematoda	+	+
Oligochaeta	+	+
Anaitides mucosa	2	-
Glycera tridactyla	1	-
Nephtys hombergii	-	1
Mediomastus fragilis	2	1
Spiochaetopterus typicus	1	3
Scalibregma inflatum	-	2
Owenia fusiformis	-	1
Myriochele oculata	-	1
Dosinia exoleta	-	1
Corbulla gibba	-	1
Abra alba	1	2
Ampelisca tenuicornis	5	-
Microprotopus maculatus	-	3
Diastylis laevis	1	-

Table 2. Macrofaunal species identified from post-harrowing diver-taken cores at Freaghillaun

Post-harrowing survey

Table 2 lists the species recorded from the cores taken along the transect. 20 species from the major taxonomic groups were collected with the Polychaeta being represented by most genera (12). At the station level, 7 species were recorded under the cages (579 individuals), 11 at the edge of the cages (341 individuals), 8 at 20 m off the cages (32 individuals) and at the 50 m station there were 14 species (29 individuals). It is of interest to note that many of the polychaete specimens collected were of sub-adult/adult size. Similarly the crustaceans were all large individuals. The bivalves however were all smaller sized individuals i.e. < 1 mm.

Table 3 presents the community parameters based on the faunal returns. Both the pre- and post-harrowing results are contained in this table.

Station	Species	Indivs.	H'	J'	SR
Pre-harrow					
Under	2	9	0.50	0.50	0.45
Edge	1	1		Not applicable	
20 m	3	4	1.50	0.95	1.44
50 m	3	13	1.59	0.80	1.14
Post-harrow					
Under	7	579	1.00	0.35	0.94
Edge	11	341	1.54	0.48	1.37
20 m	8	32	2.20	0.78	1.60
50 m	14	29	3.23	0.87	3.46

Table 3. Freaghillaun south pre- and post-harrowing survey. A comparison of community parameters of both surveys. Actual numbers of species and individuals recorded, together with the synoptic community parameters of diversity (Shannon - Wiener (H')), evenness (J') and species richness (SR) for each sampling location. Values are for combined replicate samples per station, i.e. per 0.03 m^2. Since Nematoda and Oligochaeta were not identified to any lower taxonomic level, they were excluded from these analyses.

These results show that in the pre-harrowing survey, such community descriptors as numbers of species and individuals were so low as to make diversity, eveness and species richness values meaningless. These same values however after the harrowing had taken place had returned to more meaningful levels given the historical inputs of organic material at the location.

Sediment Profile Imagery (SPI).

Values for the 6 of the 7 parameters measured from the image analysis of SPI images for both the pre- and post-harrowing survey are presented graphically in Figure 5. Parameters include sediment type, prism penetration depth, sediment boundary roughness, apparent redox discontinuity depth, infaunal successional stage and organism-sediment index. As two images were analysed per sampling location, mean values are sometimes presented. The results are interpreted here with respect to each of the measured parameters for the fishfarm site in general.

Sediment type.

The sediment classifications for each sampling site as determined from grain size comparisons. With the exception of a single sample taken underneath the cages, sediments are classed as muddy sands (i.e. a mean grain size of 0.063 - 0.125 mm).

Concerning the pre-harrowing survey, it was noted that particles in the surface sediment layers were aggregated to a greater or lesser extent but this material did not show any evidence of faunal reworking. This is taken to represent an accumulation of recently added material which has not been assimilated by the resident fauna. The layer of particle aggregations consisted of up to c. 8 cm of material underneath and at the edge of the cages and within this layer, the upper 1 to 2 cm showed a loose granular fabric while the material became more compact with increasing depth in the sediment layer. This layer of aggregated material was also detected at the 20 m site to a depth of c. 2 cm within the sediment. Below this the sediment had a more normal muddy sand appearance. At the 50 m site, a layer of loose material was also present on the surface of the sediment to a depth of 0 to 1 cm but this material contrasted in its nature with the layer of material found underneath and up to c. 20 m from the cages. From its nature, it is assumed that the surface layer of material is at least partly biogenic in origin in that it showed evidence of reworking and pelletisation due to faunal activity.

Sediments under, and at the edge of the cages in the post-harrowing survey showed a thin (ca 1 cm) layer of finer material which overlaid a more uniform muddy sand. This layer of finer material may be derived in part from bioturbating activities of the infauna or may also be due to the settling our of fines which are resuspended by tidal activity. In these images, there is also a

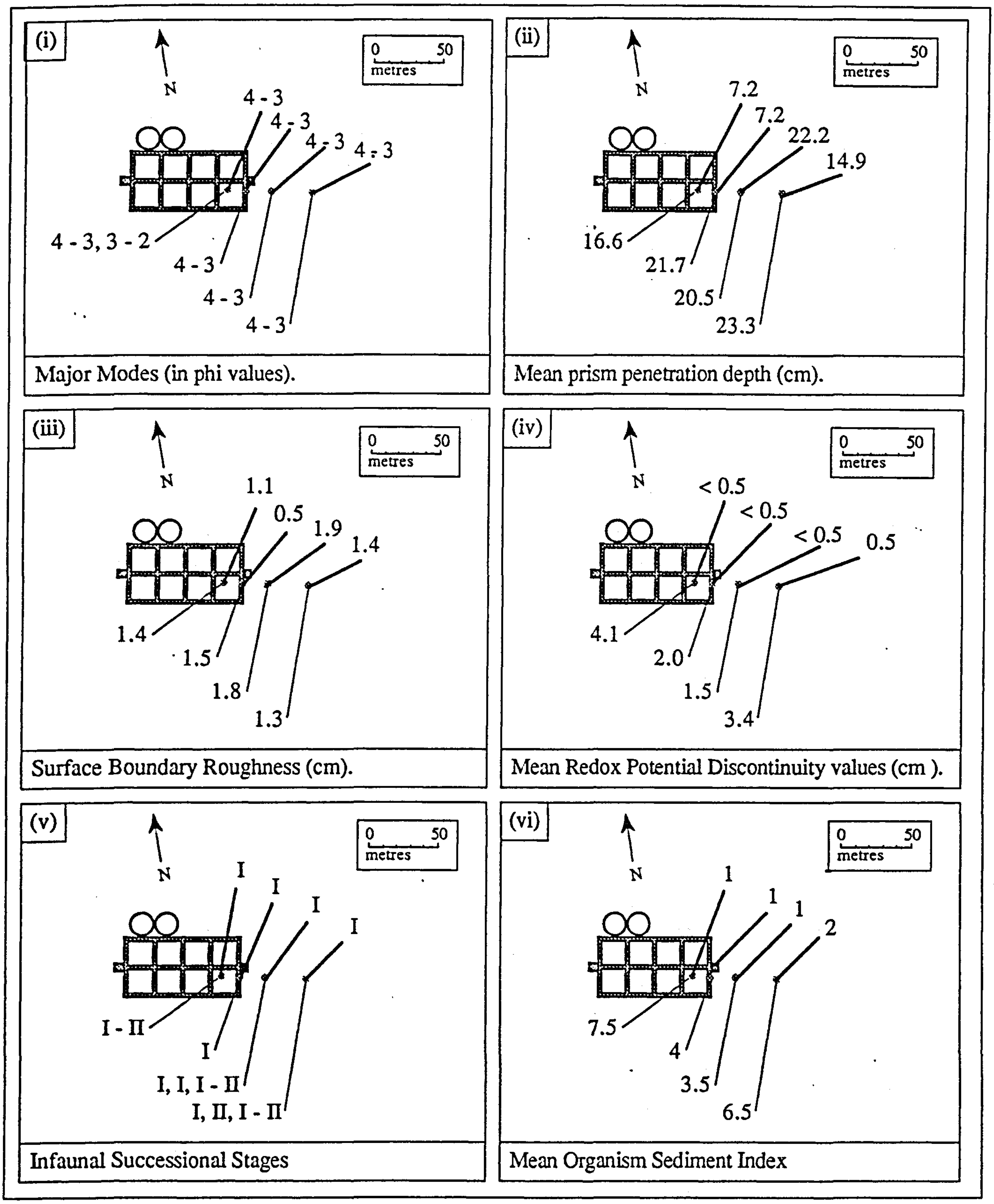


Figure 5. Sediment Profile Imagery data from pre- and post-harrowing surveys at Freaghillaun. (Upper figures relate to pre-harrow survey, lower figures to post-harrow survey).

clear trend in the colour of the sediments from under the cages to 50 m away : sediments under the cage and at the edge are light brown in colour indicating that they are relatively well oxygenated and low in excess organic matter while those at 20 and 50 m are very dark indicating that they are organically enriched.

Prism penetration depth .

It should be noted that an element of diver effort is related to the actual prism penetration depths achieved. Nevertheless, prism penetration depth on the whole is a good indicator of the degree of sediment compaction, with muddy sediments allowing for better penetration than in more compact sandy sediments.

At the Freaghillaun Turmec cage site, prism penetration depth was better during the post-harrowing survey than during the pre-harrowing study. A maximum depth of 23.3 cms was achieved 50 m off the cages during the post-harrow survey.

Sediment boundary roughness .

Pre-harrow survey.

Boundary roughness features at the Freaghillaun sites are attributed to a blanketing effect owing to the deposition of waste material where the sediment surface is loose and unevenly rough and where waste food pellets also feature on the surface. This condition was noted out to the 20 m location. The surface of the sediment also supported moderate densities of very small infaunal tubes.

Post-harrow survey.

At the under cage and edge locations, boundary roughness values are due to some reworking activity by infauna while at the 20 and 50 m locations, values are in part at least due to the presence of small, infaunal tubes of polychaetes.

Apparent redox discontinuity depth (RPD).

Pre-harrowing survey

RPD depths are calculated on the basis of differences in reflectance values of sediment layers which in turn are associated with differing aeration or oxidization conditions in the sediment. With respect to the pre-harrow investigation, there was very little differentiation in reflectance values on the sediment profile images taken around the fish cages and this made accurate determination of RPD's difficult at best and these values are indicated as < 0.5 on

Figure 5.. Images taken at these locations presented a uniformly grey appearance and were characterised by surface accumulations of waste material and a lack of macrofauna. It is suggested that under these conditions the sediments are hypoxic (i.e. lacking in oxygen) leading to reducing conditions in the sediment body and perhaps also in the overlying water body. Under these conditions it is also likely that methane and hydrogen sulphide gas bubbles will be released from the sediments. However, the loose, open structure of the sediment fabric at these locations is suggestive of a diffusion of any gases formed as an effervescence rather than as discrete gas bubbles. Such conditions are indicative of severe organic loading on the seabed.

Post-harrowing survey

The results of this survey show that redox depths were considerably deeper than during the pre-harrowing survey with the deepest RPD values being recorded under the cages (4.1 cm) and 50 m off the cages (3.4 cm). These deeper RPD depths indicate that organic material which built up over the production cycle had been dissipated between the two survey periods.

Additional biological information.

Pre-harrowing survey

With the exception of the 50 m location, the SPI images did not show any evidence of faunal activity. A large specimen of the razor shell, *Ensis*, was imaged vertically in the sediment at the 50 m location and also there were suggestions of a pelletisation of surface sediments at this location. The level of inferred faunal activity for the site in general is in agreement with the results of faunal sampling as already outlined where only 14 individuals comprising 6 species were recorded for the site as a whole and the majority of these were taken at the 50 m location.

Post-harrowing survey.

Infaunal worms, which from the core samples are presumed to be *Capitella capitata*, were noted in the images taken under the cages. Small tubes were present at the edge, 20 and 50 m sampling locations. These may either be polychaete or amphipod tubes.

Infaunal successional stage.

Pre-harrowing survey

In this survey, undercage and cage edge locations are classed as impacted Stage I communities which are characterised by a shallow redox boundary, shallow bioturbation depths and a very impoverished infauna.

Post-harrowing survey

The successional stages of the areas sampled at this period are classed as a more advanced stage and have been attributed to either a stage I - II or a stage II-type assemblage and have a deep RPD and bioturbational depths and have a relatively rich and diverse fauna.

Organism-Sediment index (OSI).

Pre-harrowing survey.

Low OSI values (i.e. ≤ 6) are indicative of locations which have experienced some recent perturbation or stress. In dealing with areas which are subject to organic enrichment, OSI values in the range +1 to +6 generally indicate an overload situation where inputs of material exceed the capacity of the system and the net result is an accumulation of organic rich material on the seabed. Low OSI values were recorded at all locations during this survey.

Post-harrowing survey.

By the time this survey was carried out, benthic conditions as reflected by the Organism-Sediment Index (OSI) had changed considerably for the better with undercage and 50 m values increasing to 7.5 and 6.5 respectively. The intermediate sampling locations at the edge of the cages and 20 m off were still showing signs of impact.

DISCUSSION

Results of this comparative study of benthic conditions before and after a sediment reworking programme had been carried out indicate that measured parameters had improved markedly between the two surveys : numbers of individuals, numbers of species and synoptic community parameters all increased following the harrowing excercise while chemical and biological parameters as documented by Sediment Profile Imagery all showed marked signs of recovery. The large numbers of sub-adult and adult forms which were collected in the post-harrow survey suggest that immigration into unoccupied, virgin habitats is an important method for benthic invertebrates to re-colonise such areas than was previously thought. Similarly, the presence of small bivalve species indicates the availability of larvae from the pelagos to the benthos at times of the year when they might not be expected.

Rhoads *et al.* (1978) describe a re-colonisation experiment using trays of sediment suspended off the sea floor in Long Island Sound and report that the greatest numbers of colonisers in the trays took place as late as November or December. In their study, Rhoads *et al.*

(1978) used a 300 μ mesh sieve to separate animals from the sediment. Had a similarly fine mesh been used in the present work, a significantly higher number of individuals and probably species would have been collected.

In terms of comparative studies, the faunal assembleges as recorded before the harrow activities are comparable in some ways to the species groups described by Pearson and Rosenberg (1978) in relation to changes in benthic infauna from impact of organic enrichment from a pulp mill.

Odum (1969) suggested that necessary human disturbance of ecosystems can be managed in such a way as to enhance productivity while maintaining a degree of environmental resiliency. The concept of using a harrowing technique to help speed up the recovery rate of sediments under salmon farms was initially mentioned by O'Connor *et al.* (1991) who suggested that it may be a useful management option when a farmer is faced with the deterioration of benthic conditions under the cages. They advised that if such a procedure is considered, due consideration should be given to the time of year at which it is carried out and tidal conditions which prevail since the harrowing action causes resuspension of sediment particles which could clog gills of commercially important mollusc species and the farmed fish themselves. Another possibility is that dormant toxic dinoflagellate spores may bloom if they are resuspended. They recommended that harrowing should be done during the winter months when temperature is lowest and light conditions are least suitable for phytoplanktonic activity and that it should also be carried out during ebb tides to ensure that dispersion of the suspended material is off-shore.

Data on recovery rates of different chemical and biological parameters under salmon farms following a fallowing period have been previously documented by Gowen *et al.* (1988), Gowen (1990) and Millar Retzer (1992). Gowen *et al.*, (1988) suggest that recovery may take anywhere from many months to years and Gowen (1990) when reviewing environmental data from a number of sources in Ireland noted that considerable improvement had occurred over a six month period at one particular location. Millar Retzer sampled 6 weeks, 6 months and 1 year after a farm in British Columbia, Canada, was closed down and found little difference between the 6 week and 6 month samples with samples being dominated by one capitellid species. The samples which were taken 1 year after closure were more similar to samples taken at a control location. Mattison and Lindén (1983), working off the Kattegat coast of Sweden, studied benthic succession under mussel longlines and indicated that only a limited recovery was noted in the benthos one and a half years after the harvesting of the mussels while Lopez-Jamar and Mejuto (1988) who followed the re-colonisation of sediments after a dredging operation in La Coruna Bay, northwest Spain, recorded that significant recovery had been achieved after 6 months. The results of this present study are in line with the findings of Gowen (1990) and Lopez-Jamar and Mejuto (1988).

In terms of site management, the results of this work show that significant beneficial results were recorded in the post-harrowing survey. The data suggest that in the case of the Freaghillaun site, the area to be harrowed should be extended out to at least 50 m from the cages. The impact of this technique should however be carefully examined for each site in order to determine the extent of the area required to be harrowed and the best tidal conditions under which the work should be carried out.

At present the use of fallowing and harrowing are not regularly part of site management plans in the marine finfish industry in Ireland. Besides the rapid increase in recovery rates of benthic conditions, these site management practices have a number of beneficial attributes which are : 1) the possibility of keeping different year classes of fish apart thereby reducing incidence of disease transfer 2) as there are no fish on site there will be no parasites present at the time of introduction of new smolts and numbers of parasite treatments may therefore be reduced and 3) levels of infectious bacteria would decline during the fallow period meaning there would be no sink for re-infection of the new smolts. These practices are therefore recommended for inshore farm locations which experience build-up of waste material under cages.

ACKNOWLEDGEMENTS

Bórd Iascaigh Mhara partly funded aspects of this project. Tully Mountain Salmon Farms gave freely of their time and resources during both phases of this study and we especially thank Mr. Kevin Murphy for his support. Thanks also to Mr. Joe Wall for assistance in field and laboratory work. Don Rhoads prepared the figures depicting the phases of enrichment under a fishfarm.

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