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Impact of fish farm deposition on maerl beds.

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COMMISSIONED REPORT

Commissioned Report No. 213

Investigation into the impact of marine fish farm deposition on maerl beds

(ROAME No. AHLA10020348)

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COMMISSIONED REPORT

Summary

Investigation into the impact of marine fish farm deposition on maerl beds

Commissioned Report No. 213 (ROAME No. AHLA10020348)
Contractor: Haskoning UK Ltd
Year of publication: 2006

Background

There is an ongoing search for marine fish farming sites that have the minimum environmental impact yet create quality produce and economic benefits. In the north and west of Scotland, candidate areas sometimes include maerl beds as these calcareous algal deposits tend to occur in areas sheltered from wave action with strong tidal water movement that may reduce the build-up of organic matter. Maerl beds are a UK Biodiversity Action Plan habitat and this report is the culmination of collaborative research between Scottish Natural Heritage (SNH), the Scottish Environment Protection Agency (SEPA) and Marine Harvest (Scotland) (MHS). Previously, it was unknown whether maerl beds would be resilient to fish farm operation, by virtue of the strong tidal flows that typify maerl grounds, or whether these habitats were easily degraded. Experimental evidence from laboratory studies has, however, shown that maerl is particularly sensitive to siltation and lowered oxygen levels (Wilson *et al.*, 2004). This study was undertaken to investigate the effects of fish farm deposition on maerl beds.

Main findings

This study undertook fieldwork in May and June 2003 to investigate the impact of fish farm deposition on maerl beds at three fish farms in Shetland, Orkney and South Uist. The study has revealed the following findings:

- All three fish farm sites had a significant build-up of feed and faeces trapped within maerl near the cages. Evidence of gross organic enrichment was recorded up to 100m away from the cage edges. The organic enrichment was found to affect a number of different aspects of the benthic community.
- Deposition from the fish farms affected the percentage of maerl on the seabed that was live versus dead. All three sites had more dead/dying maerl near to the cages than at the reference sites and at stations distant from the cages. Live maerl close to cage edges had a mottled, unhealthy appearance due to phycobilin pigment loss.
- Close to the cage edges, increased abundances of scavenging macrofauna were recorded (eg *Buccinum undatum, Pagurus bernhardus, Cancer pagurus, Necora puber, Asterias rubens*). Between 10 and 100 times as many scavenging macrofauna were recorded close to the cages than at reference sites.
- Marked reductions in species diversity of infaunal communities associated with the maerl were recorded around the fish farms in Shetland and Orkney. Organic enrichment effects on community structure were

also noted around the fish farms in Shetland and South Uist. Small scavenging species increased greatly in abundance near the fish farms, such as *Capitella capitata*, *Tubificoides benedii* and *Socarnes erythrophthalmus*. Many faunal groups were much more diverse at the reference sites than on maerl beds close to the fish farms. Small crustacea such as ostracods, isopods, tanaids and cumaceans were strongly affected by the presence of organic waste, being diverse and abundant at reference sites but impoverished around salmon cages.

- A particle tracking model (DEPOMOD (Cromey *et al.*, 1998, 2002a)) was used to predict the dispersion of fish farm particulate waste away from the fish farm cages. In contrast to the field results, DEPOMOD predicted that fish farms would have minimal impacts upon the maerl benthos, by virtue of the high current regimes found at the sites. This is likely to be due to the conditions for which the DEPOMOD model was developed and validated. The DEPOMOD model has been validated using a particulate tracer study on silty mud in sheltered sea loch conditions, which are typical under most Scottish fish farms (Cromey *et al.*, 2002b). However, it has not been validated for maerl substrata and the near bed current speeds at the three sites in this study fell outside the range for which DEPOMOD has been validated.

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Many people contributed to the success of the present study. The authors are particularly grateful to Christine Howson, Tom Mercer and Alison Shaw for the planning and execution of diving fieldwork. Eddie Coupar of C & R Diving Ltd, Shetland, Dougie Leask of Leask Marine, Orkney and Ian Campbell and Donald Walker of Marine Harvest (Scotland), South Uist for on-the-ground assistance. Pete Garwood of Identichaet Ltd is thanked for helpful discussions regarding maerl infauna and Rose Edwards is thanked for taking the scanning electron micrographs. Funding for the project was provided by SNH, SEPA and Marine Harvest (Scotland).

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1 INTRODUCTION

1.1 Aims and scope of the present study

There is an ongoing search for fish farming sites that have the minimum environmental impact yet create quality produce and economic benefits. In the north and west of Scotland, candidate areas include maerl beds as these calcareous algal deposits tend to occur in areas sheltered from wave action with strong tidal water movement that may reduce the build-up of organic matter. Maerl beds are a UK Biodiversity Action Plan habitat and this report is the culmination of collaborative research between SNH, SEPA and Marine Harvest (Scotland). This report provides information on the effects of fish farms on maerl habitats. This report presents the results from physical and biological surveys of three existing salmon farms and three reference sites in Shetland, Orkney and South Uist, Scotland.

This report aims to start the process of considering the likely effects of fish farms on maerl habitats. The purpose of this work is to assist the relevant authorities, SNH and SEPA to begin to develop wider policies in relation to the fish farm locations and potential impacts on maerl habitats. This work will be of particular relevance to the development of management measures and proposals in compliance with the EC Water Framework Directive.

This report represents the result of a collaborative project between SNH, SEPA and the salmon farming industry. The data used in the report consists of pre-existing data gathered by the project partners and additional data relating to the marine benthic communities gathered as part of this project. Accordingly, the elements of the environmental data relating to the physical data presented in section 5 provide a useful context but should be treated with some caution.

The objectives of this study were as follows:

- to review existing information on the extent of maerl beds and identify whether fish farm operations overlap with this habitat;
- to carry out baseline survey work to investigate the impacts of fish farm operations on the communities associated with maerl beds;
- to produce a report which describes the impacts of fish farm operations on the communities associated with maerl beds including distribution, species richness and diversity; and
- to produce a set of recommendations for further study that will be used by SNH, SEPA and other interested bodies to develop the most appropriate ways to regulate fish farm developments in Scotland.

The study established a programme of data collection at sites that had salmon farms located on maerl beds in order to quantify impacts to these habitats, in terms of intensity and extent, compared with reference sites. Additionally, the study involved a modelling component (using hydrographic current data and the deposition model DEPOMOD) to attempt to predict the deposition of material on the seabed. DEPOMOD is a particle tracking model, developed at the Scottish Association for Marine Science, to predict the dispersion of particulate wastes from fish farms and associated changes in benthic communities (Cromey *et al.*, 2002a, 2002b). It is currently employed by SEPA to model the dispersal of in-feed anti-sea lice chemicals and has been developed and validated for use on muddy sea loch habitats. The present study compared predictions from this deposition model with survey data to see if it could be used to accurately predict impacts at new fish farm sites or to recommend appropriate tonnage of salmon at existing maerl sites.

1.2 Fish farming background

Fish farming is a diverse worldwide industry, and is the fastest growing food-production sector in the world (Emerson, 1999; FAO, 2002). Scotland's fjordic coastline, with cool waters and strong tidal streams, is ideally suited for farming Atlantic salmon (*Salmo salar*) and this industry has closely followed the global boom in production. Since the 1960s, commercial salmon farming in Scotland increased steadily from 5000 t per year in the 1980s to over 145,000 t per year in 2002. Figure 1.1 shows fish farm sites in Scotland, which illustrates that there are now almost no major sea lochs or voes in Scotland without mariculture developments. Whilst this has provided jobs and infrastructure in remote rural areas, concerns have been raised over the environmental effects of such development. The industry and its regulators (primarily SEPA, the Crown Estates and local authorities) are working together to secure the continued sustainable development of mariculture. This is done in liaison with SNH who are consulted on relevant consent applications. Environmental concerns range from the effects of the salmon farming industry on wild salmon (eg McGinnity *et al.*, 1997), the fish caught to make salmon feed (eg Pauly, 2002), nutrient enrichment (eg, Davies, 2000; WWF Scotland, 2000), effects on predators such as seals, and the effects of chemicals used to ensure economic production (eg Grant & Briggs, 1998). However, it is the effects of organic enrichment from sea cages on maerl beds that are the focus of this collaborative project between SEPA, SNH and Marine Harvest (Scotland).

At present the mariculture industry in Scotland is heavily dominated by salmon farms, typically sited in very sheltered conditions, such as sea lochs, where the seabed is typically composed of fine sands and muds. Many of these sites were located in such locations many years previously when cage and moorings technology was not as developed as it is today. Salmon are fed a high-protein diet made up *circa* 55% fishmeal (sandeels, and other industrially caught fish) together with fish oil and cereals. It is likely that the industry will diversify over the next decade to include other top-predator finfish (eg cod and halibut) that will also need to be fed protein-rich diets. Not all of the feed pellets are eaten and the remaining material, together with fish faeces, passes through the fish cages. In sheltered, shallow conditions with slow tidal flow this organic material builds up and may remain on the seabed underneath the cages. By contrast, at deeper sites and at sites with strong tidal streams, much of this organic material is dispersed over a wider area. The effects of fish farm deposition have been well researched on muddy sea loch habitats (eg Brown *et al.*, 1987), but are poorly known for other habitats that are of conservation interest, such as maerl.

The present SEPA policy and SNH guidance on location of marine fish farming sites is to encourage the movement of cages away from enclosed areas with low current speeds to areas of moderate to high current speeds. This is to aid dispersion of wastes and lessen the potential impact of these wastes upon the seabed below and around cages. The industry has also been keen to move to areas of higher current speeds as these conditions can produce a higher quality salmon product. Accordingly there have been a number of recent applications from fish farm operators to relocate sites to these higher energy areas, some of which may be situated over or adjacent to maerl beds.

The ability of SEPA to deal with these applications, and SNH to provide advice on them, has been hindered by the lack of scientific knowledge on the impacts of fish farming upon maerl beds. At present SEPA is obliged to exercise the precautionary principle when dealing with such applications and this report is aimed at helping to better inform the decision making process.

Figure 1.1 Location of fish farms in Scotland in 2003 (data provided by SEPA)

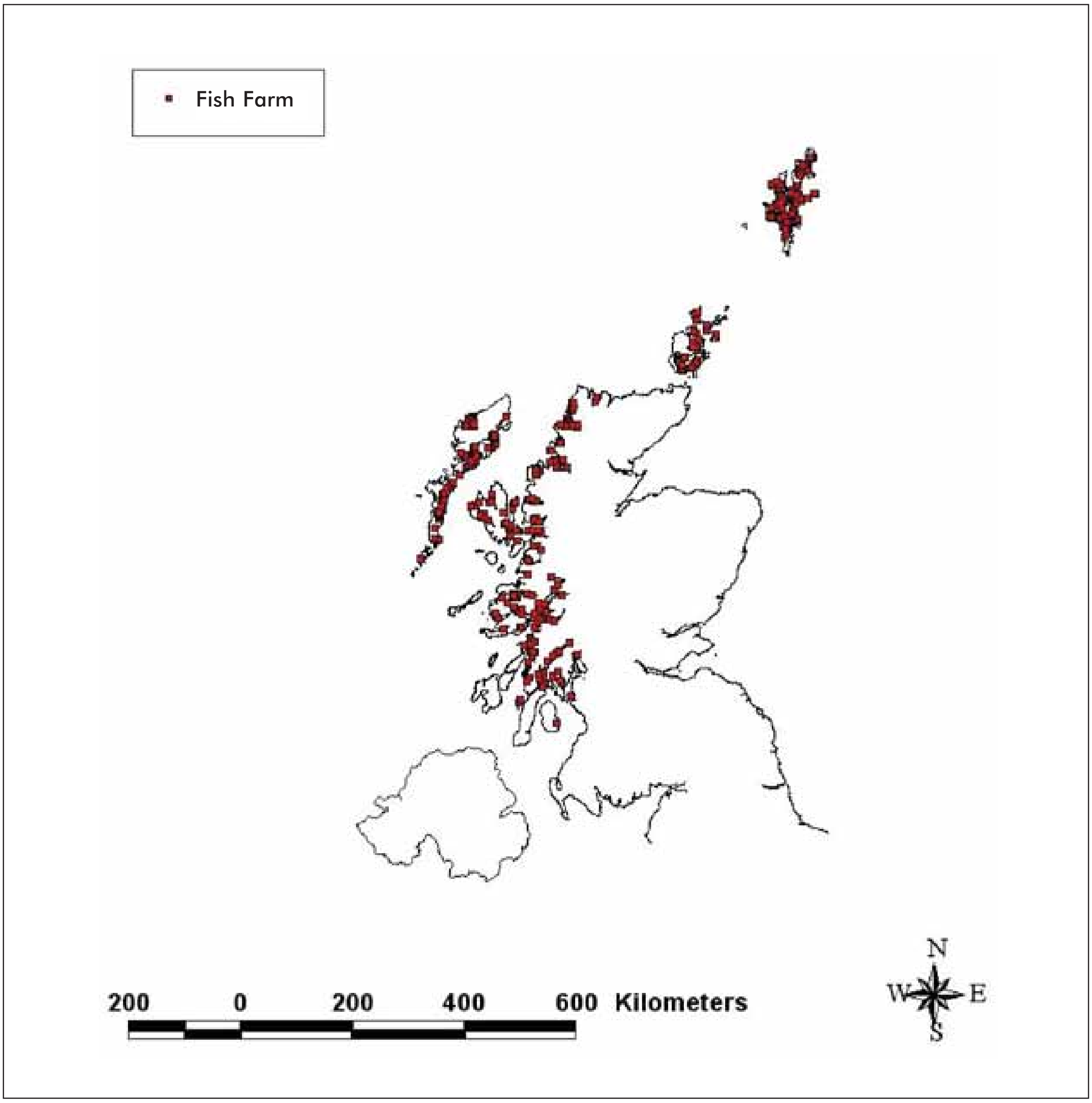
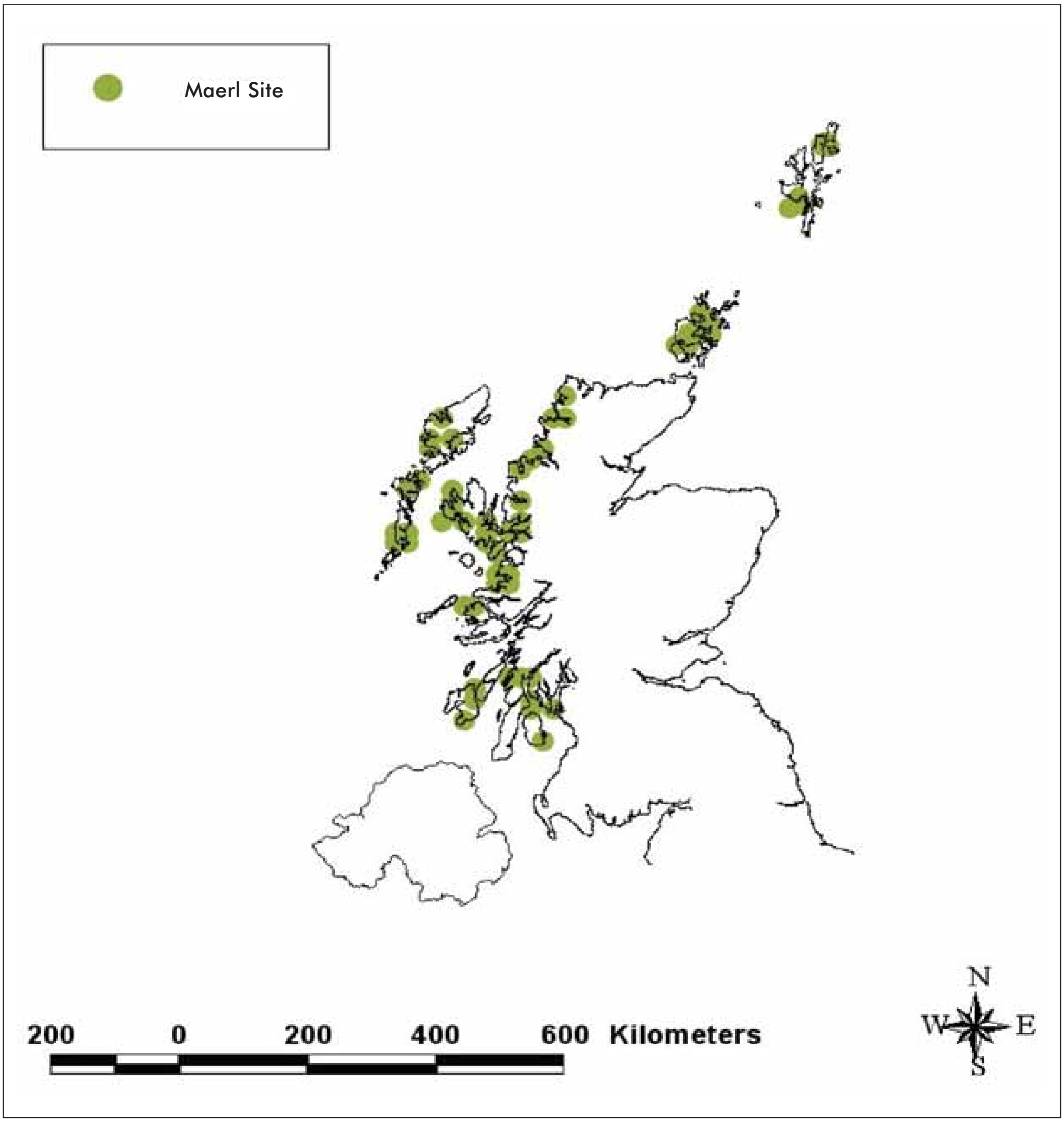


Figure 1.2 Location of recorded maerl beds in Scotland (data provided by SNH). NB Green circles represent the approximate locations of maerl beds and not the extent of maerl



1.3 Maerl background

Maerl beds are found world-wide. In the northeast Atlantic they are concentrated on the westernmost coasts. Maerl occurs in discrete areas from the Canaries and Madeira (McMaster & Conover 1966; Cabioch, 1974), NW Spain (Adey & McKibbin, 1970), Brittany (Cabioch 1970; Grall & Hall-Spencer, 2003), western coasts of the British Isles (references in Birkett *et al.*, 1998), Denmark (King & Schramm, 1982), along the Norwegian shelf (Freiwald & Henrich, 1994) to the Arctic (Kjellmann, 1883; Adey & Adey, 1973). In Scotland, they are mainly found on the western coast, Western Isles, Orkney and Shetland (Figure 1.2). Maerl is rare in the English Channel, Irish Sea, North Sea and Baltic.

Maerl forms highly diverse habitats composed of layers of loose-lying coralline red algae (Corallinales, Rhodophyta; Figure 1.3) that build up over thousands of years. These carbonate-rich deposits form sea-bed habitats with a patchy geographical distribution. The distribution of live maerl is determined by the physical conditions that favour maerl growth; they cannot withstand desiccation so are restricted to the low intertidal and subtidal, and they require light, which usually restricts production to depths less than 32m in the relatively turbid waters of northern Europe. The algae also require a degree of shelter from wave action, to prevent dispersal into deep water, but require sufficient water movement to prevent smothering with silt (Hall-Spencer, 1998). Laboratory experiments show that smothering by fine sediment and lowered oxygen levels are particularly damaging to maerl (Wilson *et al.*, 2004). Maerl is usually restricted to places such as the sills of fjords and fjards, together with the shores to the leeward of headlands and island archipelagos (Hall-Spencer, 1998, 2001a, b). The abundance of such habitats in Scotland makes it an important place in Europe for maerl, with over 242 known sites compared with *circa* 10 sites in England and Wales.

Figure 1.3 Maerl collected at 14m depth near North Bay fish farm, Loch Sheilavaig, South Uist, May 2003

Maerl-forming algae produce a heterogeneous hard substratum in various depositional environments including muddy, sandy and gravel substrata, or mixtures of these. Faunal studies show that maerl beds form isolated habitats of high benthic biodiversity and biomass (Cabioch, 1968; Keegan, 1974; Hardiman *et al.*, 1976; Bosence, 1979; Mora Bermúdez, 1980; Grall & Glémarec, 1997a,b; Hall-Spencer, 1998; BIOMAERL, 1999; Hall-Spencer *et al.*, 2003; Hauton *et al.*, 2003; Steller *et al.*, 2003) and that some support rare, unusual or endemic species of macroalgae, polychaetes and amphipods (Southward, 1957; Cabioch, 1969; Blunden *et al.*, 1977, 1981; Myers & McGrath, 1980, 1983; Maggs & Guiry, 1982, 1987, 1989; Maggs, 1983; O'Connor & Shin, 1983; De Grave & Whitaker, 1999; Clark, 2000). Maerl-forming species are amongst the slowest growing of all algae (in the order of millimetres per year), forming habitats that take millennia to accumulate (Bosence & Wilson, 2003; Grall & Hall-Spencer, 2003). This has fundamental implications for the management of activities that are likely to result in detrimental impact on maerl beds.

The conservation importance of maerl is increasingly recognised (Donnan & Moore, 2003). The European Union's Council Directive 92/43/EEC on the conservation of natural habitats and of wild fauna and flora (the Habitats Directive) gives legislative protection to Scotland's maerl with *Phymatolithon calcareum*, the main maerl-forming species in Scotland, and *Lithothamnion coralloides* included in Annex V of the Directive. This requires Member States to take appropriate management measures to ensure that any exploitation is compatible with the species being maintained at a favourable conservation status. Maerl has also been included as a key habitat for the UK within the Annex I category 'sand banks which are slightly covered by seawater at all times' such that a number of Special Areas of Conservation (SACs) designated under the Directive contain maerl beds. Maerl is also subject to a habitat action plan under the UK Biodiversity Action Plan, part of the UK Government's response to the 1992 Convention on Biological Diversity. In addition, the Oslo Paris (OSPAR) commission has engaged in the process of adding maerl bed habitats to their "List of Threatened and/or Declining Habitats and Species" (OSPAR, 2004). Apart from harbouring high biodiversity, it has been shown that the protection of Scottish maerl beds can benefit commercial fisheries. This is because Scottish maerl grounds harbour high densities of broodstock bivalves (Hauton *et al.*, 2003; Hall-Spencer *et al.*, 2003) and act as nursery areas for the juvenile stages of commercial species such as cod (*Gadus morhua*), crabs (*Cancer pagurus*) and scallops (*Aequipecten opercularis*), which are attracted to the complex three-dimensional structure (Kamenos *et al.*, 2003, 2004a,b,c).

1.4 Review of fish farm and maerl sites

As part of this study, a review was undertaken to identify areas where licensed fish farm sites in Scotland overlap with maerl. Maerl records were obtained from SNH (Figure 1.2), who had previously collated a number of data sources including published scientific papers and Marine Nature Conservation Review (MNCR) records. The locations of fish farms were provided by SEPA. Records were also obtained from SEPA on fish farm sites at which maerl had been noted as present during fish farm monitoring surveys (Table 1.1).

Interrogation of the distribution of recorded maerl beds (as obtained from SNH) in relation to the location of fish farms showed that there was only one fish farm within 100m of a recorded maerl bed. However, the SEPA monitoring records showed that there were 16 fish farm sites at which maerl had been recorded. This difference is likely to be due to the fact that maerl is under-recorded within Scotland and knowledge of its distribution is incomplete. In conclusion, there are at least 16 fish farm sites in Scotland which are known to be situated above or near maerl beds, on the west coast, in the Western Isles, Orkney and Shetland.

Table 1.1 Records of fish farm monitoring surveys undertaken by or on behalf of SEPA which have recorded maerl as being present. * indicates sites which have been surveyed as part of the present study

Site No.	Area	Description of sediment (from fish farm monitoring surveys carried out on behalf on SEPA)	Water depth (m)
1	Shetland	Sand and coarse gravel. Live maerl was present at stations 3, 4 and 5.	15–20
2	Shetland	Brown muddy sand with maerl.	18–25
3	Shetland	Light brown sand & maerl.	16
4	Shetland	Light brown sand & maerl.	19–28
5	Shetland	Maerl and yellow white coarse sand and gravel. Large patches of dead maerl present along the transects.	16–41
6	Shetland	Muddy sand and shell fragments. There were also very small amounts of maerl present.	31–38
7*	Shetland	Beige sand and maerl (approx 30–40% live).	14–15
8	Shetland	Muddy sand along the transects and at reference site 1. Reference site 2 is described as fine sand with maerl.	Not recorded
9	Orkney	Grey brown sand and stones with maerl at 5–45m from cage edge and a small amount of dead maerl at cage edge. The maerl under the cages was also dead.	14–18
10	Orkney	Sand overlain with a layer of maerl. This maerl community looks reasonably healthy in places and in fact extends right to and under the cages themselves. The main feature of the epifaunal community is the maerl bed which extends throughout the entire length of this survey. The bed would appear to be in a healthy condition.	20–21
11	Orkney	Coarse gravel, shell and maerl overlaid by algae.	11.5
12*	Orkney	Brown sand with maerl. High energy area with coarse sand shell and maerl bottom.	18 12
13*	Western Isles	A dense maerl bed overlain with red algae. There are some sandy areas. The maerl seems to be in a 'healthy' state as can be seen from the video pictures.	Not recorded
14	Western Isles	The seabed appears to consist of well sorted stones/gravel. Maerl was present between stns. 5–7.	Not recorded
15	North Highland	Maerl was possibly present ~70–80m along the transect. Coarse seabed, consisting of a mix of sand, gravel, stones & shell. Any maerl present was in small patches, & did not form large beds.	25
16	West Highland	Firm mud with shell gravel, with many mussel shells near the cage edge going out to station 2. Maerl appeared to be present at station 8 but the video was too far from the seabed to confirm this.	Not recorded

2 FIELD DATA COLLECTION

In February 2005 there were over 470 consented fish farm sites in Scotland (although only 371 are active at this time), of which 16 were known to be sited on maerl beds. From these 16 sites, three farms were chosen for study, located in Shetland (North Sandwick, Yell), Orkney (Puldrite Bay, Wide Firth) and South Uist (North Bay, Loch Sheilavaig) to obtain a wide geographical spread. None of these farms had recently been using licensed anti-sea lice therapeutants which could otherwise complicate the study of the effects of the farms since they are, in the correct concentration, toxic to Crustacea, an important component of the fauna within maerl beds. At each site, surveys were made by a team of four experienced marine biologists (Jason Hall-Spencer, Christine Howson, Tom Mercer and Alison Shaw) using scuba diving between 24 May–29 June 2003.

In the presentation of the data gathered and analysed as part of this work it is important to note that the data are used to compare within site conditions and not between the sites. In this way the use of previously obtained data is valid as it provides a useful context to the survey data.

2.1 Survey areas

2.1.1 Shetland

The northernmost area surveyed was in the Shetland Islands (North Sandwick, Yell) at a salmon farm operated by Thompson Brothers Salmon. Fish farming began at this site in May 1991 and seabed monitoring was started by C & R Diving Ltd., Voe, Shetland in June 1991. As part of the current study, copies were obtained of annual seabed monitoring reports for the site from 1990–1996 and SEPA monitoring reports for 1991–2003. These reports provide details of the history of use of the site, as well as a summary of seabed conditions and have been used to provide the context against which the results of this study have been compared.

Diving surveys of this site were carried out on 24–26 June 2003. The farm is situated in an east-facing bay on the north-east coast of Yell (Figure 2.1) and is sheltered from prevailing south-westerlies, but more open to the north-east. The site was consented for a maximum standing biomass of 995 t and, at the time of the survey, was stocked with salmon in the second year of production. The site was composed of eight circular cages, anchored in a grid system (Figure 2.2) in approximately 13–16m depth of water. The fish were fed by a pneumatic delivery system controlled by a moored feed barge.

Figure 2.1 Location of North Sandwick farm and reference sites off Yell, Shetland, June 2003

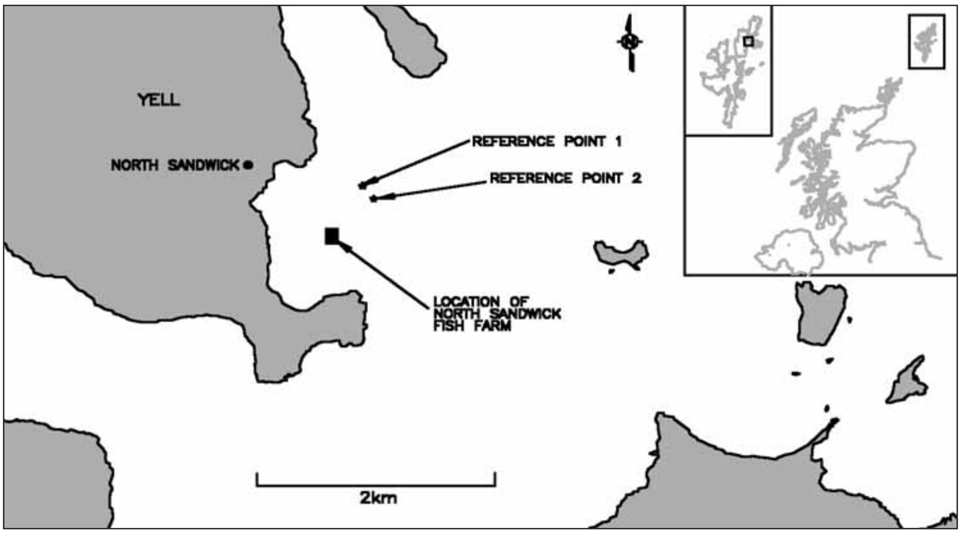
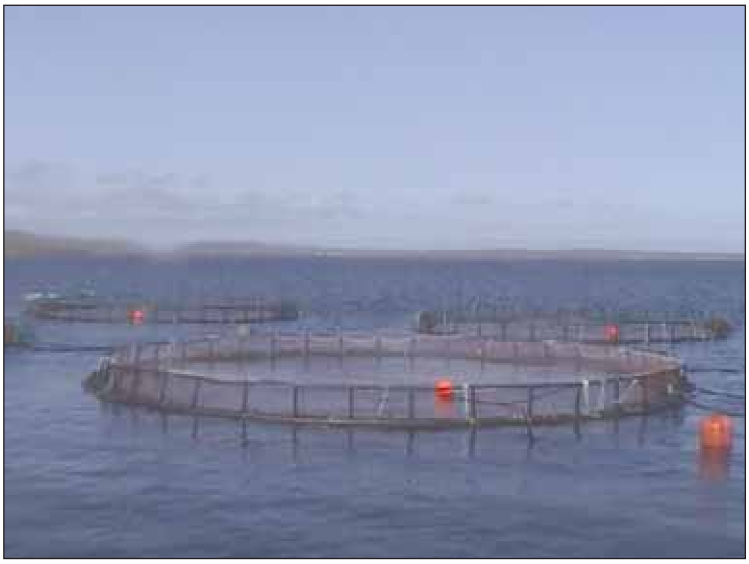


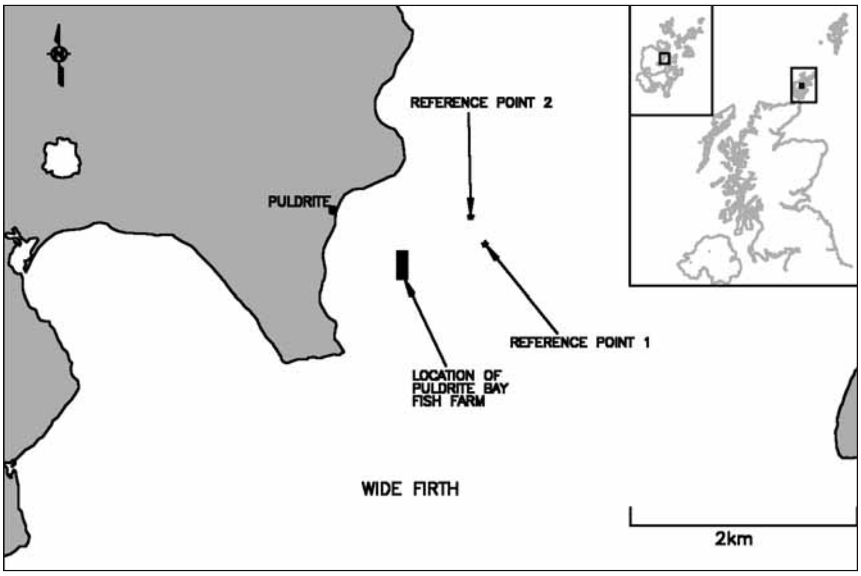
Figure 2.2 View of circular cages used at North Sandwick salmon farm, Yell, Shetland, June 2003



2.1.2 Orkney

The Orkney fish farm was located in Puldrite Bay in Wide Firth and operated by Orkney Seafarms Ltd. Fish farming began at this site in 1993 and SEPA fish farm monitoring reports have been reviewed for 1998 and 2001. This farm was surveyed on 28–29 June 2003 and had been consented to stock up to 980 t of salmon. Like the Shetland site, this farm comprised circular cages anchored by extensive mooring cables. The site was located in the north-western corner of Wide Firth (Figure 2.3) and sheltered from the prevailing south-westerlies. Cages were situated in approximately 15m of water depth and exposed to strong tidal streams. Smolts (*cf.* adults) were being fed by hand from a boat and the cages had recently been moved inshore onto a predominantly sandy seafloor with scattered maerl. At the time of survey there were eight cages with space for a further four within the existing mooring system.

Figure 2.3 Location of Puldrite Bay fish farm and reference maerl stations, Orkney, June 2003



2.1.3 South Uist

The South Uist site was in the sheltered waters of Loch Sheilavaig on the east coast of the island (Figures 2.4 and 2.5). Within the loch there were three groups of cages operated by Marine Harvest (Scotland), with the North Bay group being situated towards the loch entrance. As part of this study the North Bay fish farm site was surveyed by Royal Haskoning on 24–26 May 2003. In addition, grab sampling was undertaken by Gardline Ltd on 19 June 2003 as part of routine fish farm monitoring. Fish farm monitoring reports were obtained for this site for 1999 and 2001–2003. In 2003, the farm was consented for a maximum biomass of 311 t and had been in operation for a number of years at this biomass limit. The farm comprised rectangular metal cages (*cf* Shetland and Orkney sites) and fish were fed from automatic hoppers fitted to each cage. The cages were sheltered from wave action in all directions, being surrounded by a network of small islands on all sides. The cages were situated over maerl in approximately 10–15m of water and are understood to have not been moved since the late 1990s.

2.2 Methods

The survey design was specified in the project brief and was based on the survey methods routinely recommended by SEPA for the extended monitoring of marine cage fish farming, as described in SEPA (2003). The impact of the salmon farms on seabed communities was investigated by examining a number of parameters which describe the biological and physico-chemical status of the seabed. These included the particle size distribution, sediment chemistry, visual appearance of the seabed, percentage live versus dead maerl and structure of the infaunal community. In addition, some samples of maerl thalli were examined by scanning electron microscope (SEM) to identify the species and condition of the maerl thalli. A list of the sampling undertaken at each site is presented in Table 2.1. It should be noted that the sampling strategy differed slightly at each site. For example, at South Uist the visual observations and percentage live versus dead maerl was recorded by Royal Haskoning in a similar arrangement to the other sites, however at this site the infaunal community was sampled by grab, rather than core as part of routine fish farm monitoring by Marine Harvest (Scotland). As such, samples at South Uist were taken from pre-designated sites which had been sampled in previous years rather than sites selected specifically for this project.

At Orkney and Shetland, samples were taken along four benthic transects running out from the fish farm cages, as shown schematically in Figure 2.6. Two of these transects were 100m long and were situated in line with the predominant current direction. The remaining two transects were situated at right angles to these. At South Uist, the sampling strategy varied slightly due to the geography of the site. Given the resources available and the developmental nature of this project this intensity of sampling was considered sufficient to allow effective gross comparison within the sites. In order to provide comparison, surveys were also made at reference sites, which were similar maerl sites that were located between 500m and 1km away from the fish farms and unlikely to be influenced by heavy organic loads from the farms. As the project was focussed on the effects and status of the maerl beds in the area of this fish cages, the reference sites were chosen to represent local maerl bed sites that are comparatively remote from the influences of the fish farm.

Figure 2.4 North Bay farm and reference sites, Loch Sheilavaig, South Uist, May 2003

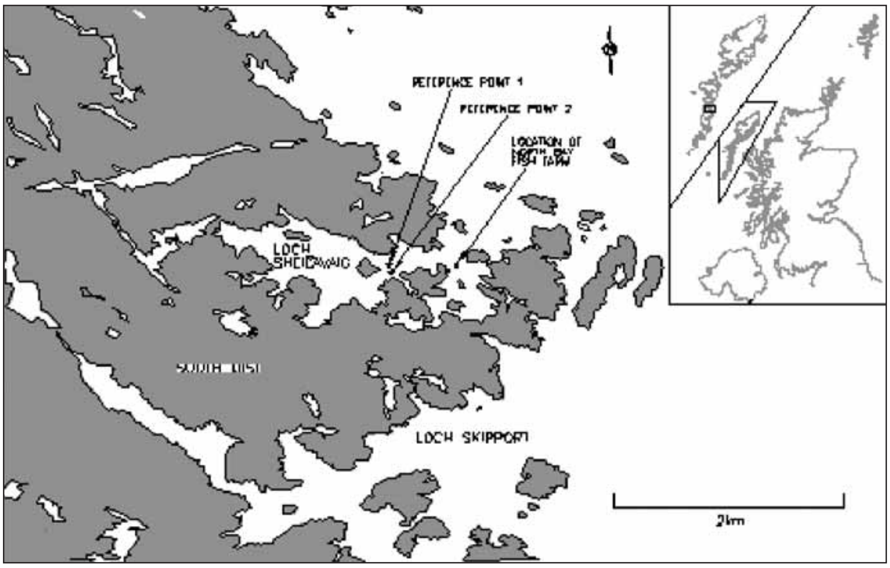
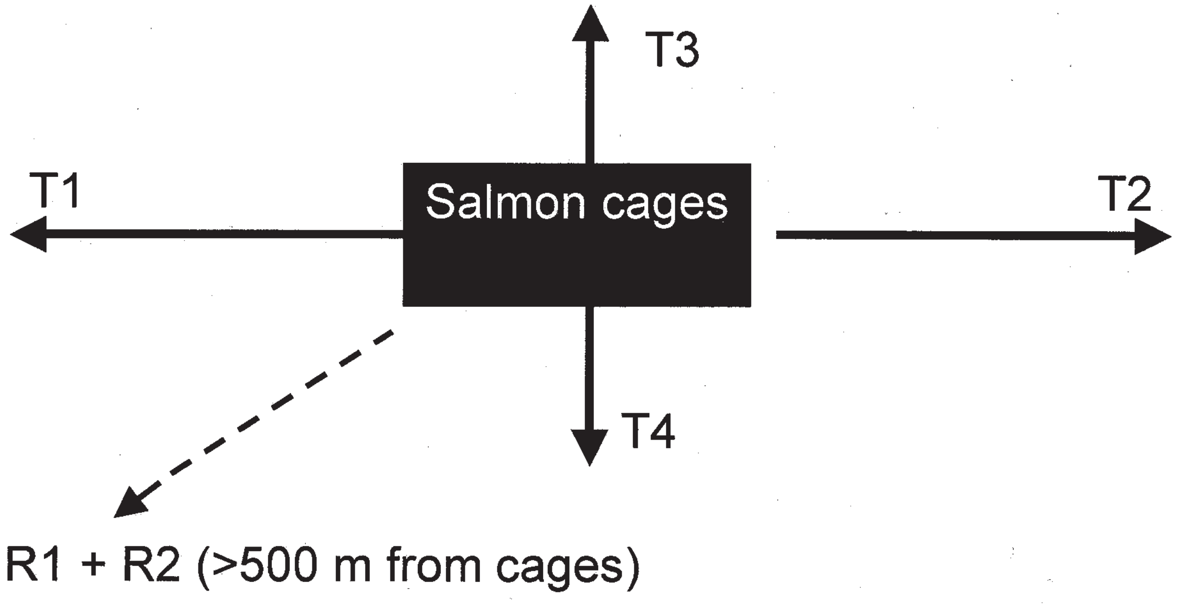


Figure 2.5 View of fish farm at North Bay, Loch Sheilavaig, South Uist. Rather than using antifoulant chemicals on the nets, the farm workers are seen using a labour-intensive method of cleaning the nets. The upper 3m of the net is lifted out for a few days, causing fouling organisms (eg seaweeds and hydroids) to die and drop off the nets

Table 2.1 Summary of survey work undertaken. MHS = Marine Harvest (Scotland), RH = Royal Haskoning and SEPA = Scottish Environmental Protection Agency

Type of survey work		**Survey site**	
	North Bay, Loch Sheilavaig, South Uist	**North Sandwick, Yell, Shetland**	**Puldrite Bay, Wide Firth, Orkney**
Particle size analysis	Gardline Ltd	–	ALcontrol Ltd
Sediment chemistry (Total organic carbon, Cu, Zn)	–	–	ALcontrol Ltd
Particle deposition modelling	MHS/SEPA	MHS/SEPA	MHS/SEPA
Assessment of visible effects on the benthos (% live/dead maerl and visual assessments)	RH	RH	RH
Maerl sampling and scanning electron microscopy	J Hall-Spencer	J Hall-Spencer	J Hall-Spencer
Infaunal sample collection (cores/grabs)	MHS (grabs)	RH (cores)	RH (cores)
Benthic sorting and identification	Gardline Ltd	Identichaet	Identichaet

Figure 2.6 Schematic diagram showing sampling strategy. Samples were taken on four transects (T1–4) running out to a distance of up to 100m from salmon cages, and at two reference maerl sites (R1–2) which were between 500m and 1km distant in locations of similar exposure, depth and maerl habitat



During all surveying by Royal Haskoning, positions of reference and fish farm sampling stations were recorded using a hand-held global positioning system (GPS, Garmin E-trex) from survey boats, with accuracy estimated at +/− 10m using WGS84 datum. Fish farm sampling stations were located by laying out tape measures or weighted transect lines from the edges of the cage mooring buoys to stations at 0m, 25m, 50m and 100m. Sampling locations are listed in Tables 2.2 and 2.3; transects ran from as close to cages as was considered safe, to avoid divers becoming snagged in nets.

The following sections detail the methods that were used to examine the various aspects of the seabed.

Table 2.2 Location of sampling stations surveyed by Royal Haskoning in Shetland, Orkney and South Uist between 24 May–29 June 2003

Site	Direction of transect away from cage edge	Distance and direction from cages or co-ordinates of sampling stations (Latitude and Longitude (WGS84))
Shetland Transect 1	270°	Cage edge, 25, 50, 75, 100m
Shetland Transect 2	90°	Cage edge, 25, 50, 75, 100m
Shetland Transect 3	0°	25, 50m
Shetland Transect 4	180°	25, 50m
Shetland Reference 1	–	60.64970598 N – 0.9837125 W
Shetland Reference 2	–	60.64904776 N – 0.9824736 W
Orkney Transect 1	45°	25, 50
Orkney Transect 2	225°	Cage edge, 25, 50, 75, 100
Orkney Transect 3	135°	25, 50m
Orkney Transect 4	315°	25, 50m
Orkney Reference 1	–	59.04913578 N – 2.99330334 W
Orkney Reference 2	–	59.04725244 N – 2.99123573 W
South Uist Transect 1	35°	Cage edge, 25m, 50m, 75m, 100m
South Uist Transect 2	225°	Cage edge, 25m
South Uist Transect 3	135°	Cage edge, 25m, 50m
South Uist Transect 4	315°	Cage edge, 25m, 50m
South Uist Reference 1	–	57.34620 N – 7.24739 W
South Uist Reference 2	–	57.34603 N – 7.24778 W

Table 2.3 Location and details of 0.1m^2 van Veen grab sampling stations at Loch Sheilavaig, South Uist, June 2004

Sample Number	Distance to cages	Grab volume (litres) (grab 1 / grab 2)	Water Depth	Latitude & Longitude (WGS84 decimal)
9	50m	4 / 3	4m	57.3469 N – 7.237617 W
10	25m	5 / 6	6m	57.34677 N – 7.239 W
11	0m	6 / 4	10m	57.34655 N – 7.23825 W
12	Reference	10 / 5	9m	57.34647 N – 7.248617 W
13	Reference	6 / 9	5m	57.35183 N – 7.232133 W

2.2.1 Particle size analysis

Samples were taken for particle size analysis in order to characterise the sediments. In Orkney and Shetland, divers collected samples for particle size analysis in 100ml plastic pots from the sediment surface (0–2cm) at each sampling station. These were analysed by ALcontrol Ltd by dry sieving. In South Uist, subsamples of sediment were taken from the van Veen grabs and were later analysed by Gardline Ltd by sieving.

2.2.2 Sediment chemistry

In Orkney, three samples (each 50ml) of sediment were collected from the sediment surface (0–2cm) for chemical analyses at each station. These samples were taken by scooping the sediment surface with a sample jar. The samples were stored in an airtight container, frozen and transported to the laboratory for analysis. The samples were analysed by ALcontrol Ltd for total organic carbon, copper and zinc, in accordance with United Kingdom Accreditation Service (UKAS) accredited procedures. The loss on ignition (LOI) method was used to measure total organic carbon, which was undertaken at 450°C for 4 hours.

Redox measurements were taken at the sites in Orkney and Shetland. Redox profiles were taken from two of the core samples collected for the benthic analysis at each survey station. Measurements were made immediately on collection of the sample using a portable redox meter with a combination oxidation-reduction potential (ORP) platinum electrode. Where possible, measurements were made at 1cm intervals from the surface to the depth of the core (ie 20cm). However, it was found that due to the open nature of the maerl habitat, no meaningful results were recorded most likely due to water being able to penetrate through the substrate. Therefore the redox measurements have not been discussed further in this report.

2.2.3 Particle deposition modelling

The particle tracking model, DEPOMOD, was used by SEPA to predict solids deposition on the maerl beds and associated changes in their benthic communities. The model requires an input of good quality current data within the vicinity of each site (collected within 150m of the site centre). These data need to be representative of the water column, particularly near the seabed (within 4m of the seabed) as this is important for predicting the resuspension of particles.

Current meter information was examined from all three sites. However, only the data recorded at the Shetland site were acceptable for modelling purposes. At this site hydrographic information was available from an array of three current meters deployed at 3.2, 7.7 and 10.7m above the seabed 150m from the centre of the fish farm on 7–28 June 2002. Bathymetric chart data were used to create a model grid 1km^2, onto which were added cages representative of the Shetland site. Thus the particle tracking, resuspension and benthic modules of the DEPOMOD model were applied, for the Shetland site using two feed-load scenarios;

- 297 kg/pen/day (representing the known feeding regime in March–May 2003), and
- 698 kg/pen/day (representing the maximum feed input in 2001–2002).

The model was used to predict two measures of benthic impact; solids deposition and infaunal trophic index (ITI) that were then compared against benthic impacts recorded in the field. ITI index scores reflect changes in the composition, abundance and feeding-types of infaunal assemblages. The ITI is routinely used by SEPA in its assessments of fish farm impact and was developed as a tool to assess the pollution status of UK coastal sediments (Codling & Ashley, 1992).

Insufficient hydrographic data were available for either the Orkney or the South Uist sites and therefore DEPOMOD model runs were not undertaken for these locations.

2.2.4 Assessment of visible effects on the benthos and live versus dead maerl

At each survey station, divers recorded sediment characteristics such as colour, physical consistency (sand, mud, shell, gravel), texture (soft, firm), presence of feed pellets and *Beggiatoa* fungal mats. Comments were also made on any other physical features that were obvious from the visual assessment, eg the presence of mega-ripples, fish farm litter and level of disturbance. In addition, conspicuous epifaunal species were noted and their abundance estimated. A Sony PC-110 digital video camera (in a Sea & Sea VXPC110 housing with NiteRider High Intensity Discharge lights) was used to provide a record of seabed conditions around each of the fish farms and reference maerl stations. A 100 x 1m strip of the seabed was recorded along transects running up to farms and along the centre of reference sites, and subsequent transcripts were made when analysing the videos.

Two methods were used to assess the abundance of live versus dead maerl at the survey stations. Replicate 50cm x 50cm quadrats (n = 3), divided into 10cm x 10cm squares, were dropped haphazardly on the seabed at each sampling station. The percentage cover of maerl, shell gravel, and silt was first recorded by divers onto underwater slates, along with the cover of waste food, faecal pellets, and *Beggiatoa* mats. Divers also estimated what percentage of the maerl cover was live. Whole quadrats (or four pictures of quarters of quadrats) were then photographed using diver-operated stills cameras (E20 Olympus digital SLR with wide angled lens and Titan housing or Nikonos V cameras with 35mm slide film). Finally, 10cm x 10cm squares within each quadrat were filmed using video to provide a permanent record.

2.2.5 Maerl sampling and scanning electron microscopy

In order to identify the maerl species and assess the condition of the maerl thalli, maerl samples were collected from quadrats at stations next to the cages, 50m from the cages and at reference sites. These were later examined microscopically (first at x40 magnification dissection light microscopy then at x2200 SEM) to determine their taxonomic identity and their condition (by examining their phycobilin pigmentation and the structure of the surface layer of cells). Methods for taxonomic identification followed those of Irvine & Chamberlain (1994) using a JSM 5600 LV SEM at the University of Plymouth.

2.2.6 Infaunal sample collection and benthic sorting and identification

In Shetland and Orkney, samples were taken for analysis of macrofauna by Royal Haskoning via diver-operated cores following Procedural Guideline No 3–8 of the Joint Nature Conservation Committee Marine Monitoring Handbook (Brazier, 2001). Five cores were taken at each station using 11cm diameter cylindrical capped cores (approximately 0.01m^2) to sample sediment to a depth of about 20cm. As soon as possible after sample collection, core samples were double bagged and preserved using borax buffered formo-saline solution (50g sodium tetraborate in 2.5 l of 40% formaldehyde solution, diluted by 2–3 times to give 15–20% formaldehyde) for later laboratory sieving and analysis.

For the samples from Shetland and Orkney, sample sorting and identification were undertaken by Peter Garwood of Identichaete. Samples from Orkney were sieved using a 1mm mesh, whereas samples from Shetland were separated using a 1mm mesh and a 0.5mm mesh in order to provide a comparison of the two methods. Following sieving, the resulting fraction was elutriated with fresh water to float off lighter faunal elements. This elutriate was then examined using a dissecting microscope, extracting, identifying and counting the various species present. The heavy elements remaining after the elutriation process were scanned under low magnification and any remaining fauna removed, identified and counted. Where necessary, appropriate preparations of whole animals or parts of them were made and examined under a compound microscope.

In South Uist, Marine Harvest (Scotland) collected 0.1m^2 van Veen grab samples in June 2003 to conform with requirements of its discharge consent. Sampling was undertaken by grab rather than diver-operated cores. Pairs of grab samples were taken at distances of 0m, 25m and 50m north of North Bay fish farm and from two local reference sites. These were pre-designated sites which had been sampled in previous years rather than sites selected specifically for this project. Details of the sampling undertaken are presented in Table 2.3. The grab samples were sieved using an auto-siever using a 1mm mesh then preserved in 10% borax buffered formalin.

Sorting and identification of the samples from South Uist were undertaken on behalf of Marine Harvest (Scotland) by Gardline Ltd using the following method:

- preserved samples were washed with freshwater on a 1mm sieve to remove traces of formalin, placed in gridded white trays and then hand sorted to remove all fauna;
- sorted organisms were preserved in 70% Industrial Methylated Spirit (and 5% glycerol);
- where possible all organisms were identified to species level according to the nomenclature of Howson & Picton (1997);
- colonial and encrusting organisms were recorded by presence alone;
- sorted residue was returned to 4% saline formalin and stored;
- estimated counts were undertaken on those samples with very high numbers of a few dominant species (generally this affected only three or four species in a sample);
- material retained after sieving at 1mm was spread evenly over a gridded white tray (marked with numbered squares) and the fauna from a percentage of squares (routinely 20%) removed for detailed identification. Relevant squares were chosen using random number tables;
- the remainder of the sample was placed in a petri dish (or number of petri dishes) and examined under a binocular microscope. All individuals of non-dominant taxa were removed, identified and enumerated in the normal way (numbers were not estimated). Numerically dominant species numbers were estimated for the whole sample by dividing taxa counts by the sub-sampling percentage;
- allocation of ITI feeding groups to individual taxa was based on Codling & Ashley (1992) and WRc (1997). Assessment of the feeding group was not possible for a few of the taxa where little is known of their feeding behaviour.

2.3 Quality assurance

In order to ensure that the project was undertaken in a robust and thorough manner, the following measures were taken to ensure the quality of the data:

- the project was managed by Royal Haskoning, who are ISO 9001 accredited, following the processes laid down in their quality management system;

- the diving work was carried out by a team of four experienced marine biologists. Three of the divers have carried out surveys of this type for at least ten years and are very experienced with the *in situ* identification of infauna and red algae. In addition, they have been trained in standard marine monitoring survey techniques, such as the MNCR Phase 2 surveys. In order to ensure consistency in the surveys, the same survey team was used at each site;
- prior to undertaking the visual assessment of percentage live versus dead maerl, the survey team undertook a quality control exercise, whereby each diver assessed photographs and compared their findings, to ensure the same method was used by each team member;
- following each survey, the results of the visual observations were checked by the project manager for anomalies;
- particle size analysis and analysis of sediment chemistry were carried out by a UKAS accredited laboratory, which is also accredited to BS EN 17025;
- the infaunal samples from Shetland and Orkney were sorted and identified by Peter Garwood of Identichaet, who participated in the National Marine Biological Analytical Quality Control (NMBAQC) scheme;
- statistical analysis and interpretation of the data were undertaken by SEPA and Jason Hall-Spencer.

3 RESULTS: ANALYSES OF PHYSICAL DATA

3.1 Particle size analyses

In Orkney, reference maerl beds were highly heterogeneous sediments with up to 75% calcareous gravel (>2mm particle size) and less than 2% silt (<0.0625mm) (Figure 3.1). The salmon farm was surrounded by mainly sandy sediment which was finely rippled by bottom currents. Scattered maerl thalli formed up to *circa* 40% of some surface sediment samples but most were dominated by sand fractions. Particle size analyses showed no significant change in the silt composition of the upper 2cm of sediment. Full data sets for particle size analyses (PSA) are provided in Appendix A. The results of the PSA contrast with the diver observations which recorded high concentrations of fine particulate matter within the immediate vicinity of the cages. This anomaly is likely to be due to the method used for the PSA (dry sieving), which does not accurately record the percentages of fine silts.

In South Uist, the sediment was dominated by medium sized particles with approximately equal percentages of gravel sized particles and silt (Figure 3.2). The survey team noted that the sediment at the stations comprised a mixture of maerl and shell sand.

At all three locations, surveyors noted that subsurface sediments close to cages were clogged with fine sediment and were anoxic (appearing black and smelling of hydrogen sulphide in the cores) but that at the reference sites the maerl formed a well-oxygenated open lattice structure.

Figure 3.1 Sediment particle size compositions recorded at reference sites and on transects around fish farm cages in Orkney, June 2003. Station numbers refer to transect number and distance from cages, eg T1–25 was transect 1, 25m from the cages

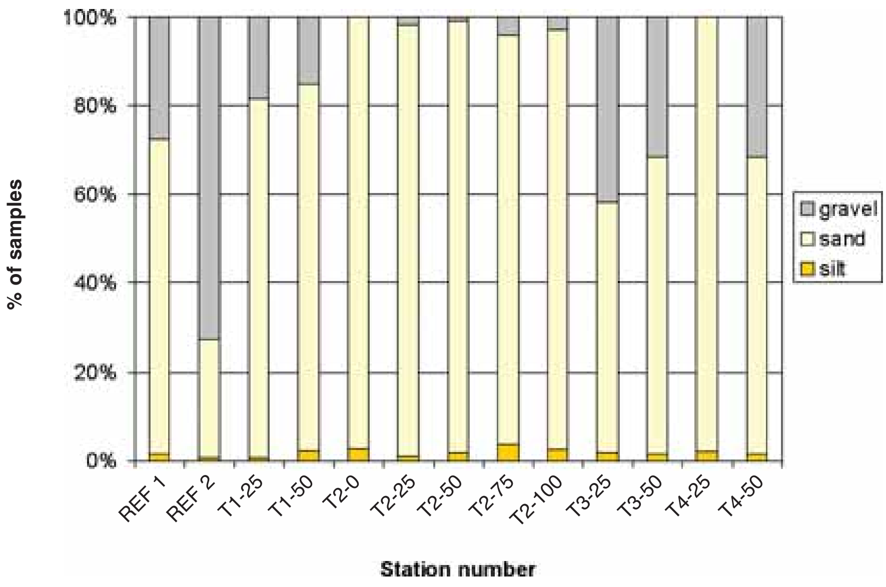
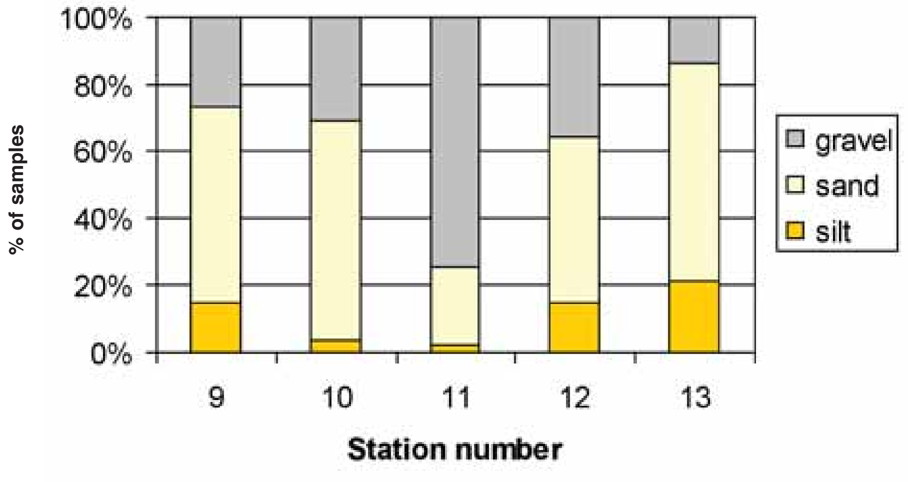


Figure 3.2 Sediment particle size compositions recorded at reference sites (Stations 12,13) and on a transect (Stations 9–11) from the fish farm cages in North Bay, South Uist, June 2003



3.2 Sediment copper, zinc and carbon analyses (Orkney)

Full survey results for copper, zinc and total organic carbon from surface sediment samples from Orkney are presented in Appendix B and summarised in Table 3.1. Samples for chemical analysis were not taken from either the Shetland or South Uist sites.

The pre-existing data on the sediment chemistry from Orkney have been compared to sediment quality criteria for marine fish farms from SEPA (2003) which are shown in Table 3.2. The criteria form a series of action levels which are considered to be typical of a grossly polluted site and above which SEPA is likely to take action. All data at the sites in Orkney are below the actions levels used by SEPA, indicating that they are not significantly polluted. No data exist for sites in Shetland or South Uist and no new samples could be collected as part of this study.

Table 3.1 Summarised chemical data from Orkney maerl sites (June 2003) Figures refer to ranges and where there is one figure all data were identical

Element	Units	Ref 1	Ref 2	T1	T2	T3	T4
Copper	mg/kg	2	12	3	3–6	3	3
Zinc	mg/kg	12	12	15–18	15–24	13–19	11
Organic carbon	%	1.1	1.5	0.4–0.8	1.5–2.4	2.6–2.9	1.7–1.8

Table 3.2 Sediment Quality Criteria: Action Levels from SEPA (2003)

Determinand	**Action level within allowable zone of effects**		**Action level outside allowable zone of effects**
Copper	Probable effects: 270mg/kg dry sediment	Possible effects: 108mg/kg dry sediment	34mg/kg dry sediment
Zinc	Probable effects: 410mg/kg dry sediment	Possible effects: 270mg/kg dry sediment	150mg/kg dry sediment
Organic carbon	9%		–

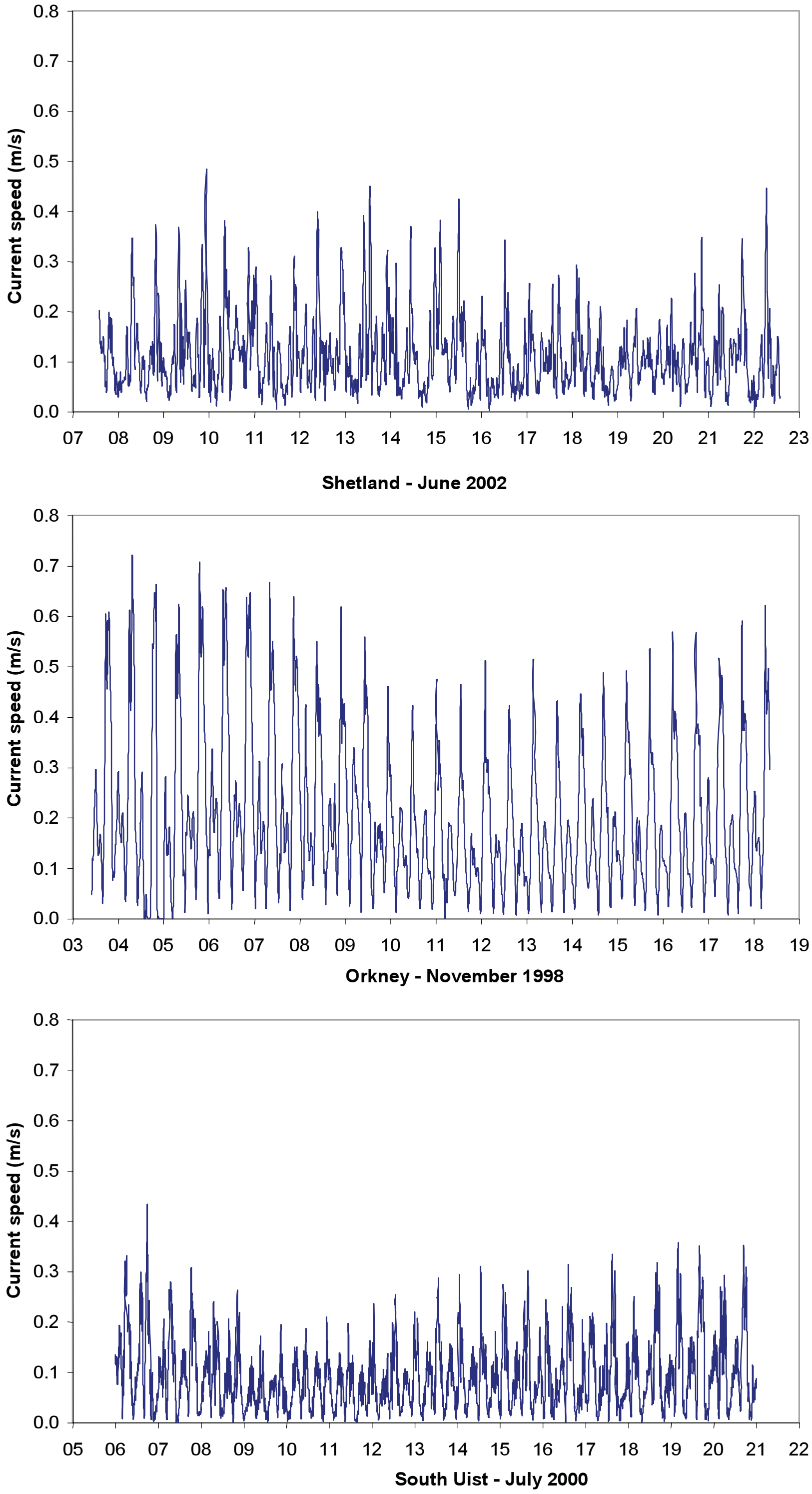
3.3 Hydrographic data

The hydrographic data used in this study were obtained from SEPA's archives of information held for Control of Pollution Act 1974 (CoPA) applications. These consisted of current speed and direction in the vicinity of the farm. While these provide a broad indication of the current regimes in the area, the data for Orkney and South Uist were not considered suitable for modelling purposes. This is because the South Uist current data were obtained at one point in the profile, 4.5m above the seabed and the Orkney current data were collected 600m away from the cages at two unknown depths. Only the data that SEPA hold for North Sandwick, Shetland were considered suitable for modelling purposes.

In spite of the limited availability of hydrographic data, there are some general points that can be made about these three sites:

- during fieldwork, divers noted strong currents at all of the maerl beds studied, both under fish farms and at the reference sites. Current meter data confirmed this, with peak near-seabed values of around 0.5ms^{-1} for the Shetland site, 0.7ms^{-1} for Orkney and 0.4ms^{-1} for South Uist;
- these seabed data show strong tidal variations in current speeds with high peak flows and regular periods of slack water-flow over much of the tidal cycle (Figure 3.3);
- recorded current speeds for a 15-day survey period at the Shetland fish farm site had means of 0.113, 0.118 and 0.122m per second and maxima of 0.213, 0.205 and 0.486m per second for heights of 3.2m, 7.7m and 10.7m above the seabed respectively. Surface currents can often be faster than seabed currents due to the accelerating influence of prevailing winds on surface water and the decelerating influence of seabed friction on bottom water currents;
- it should be noted that the seabed current speed, at the Shetland site, was over the threshold for resuspension (9.5cm/s) for 52% of the time. The most dispersive site that DEPOMOD has been validated for exceeds the threshold for only 26% of the time.

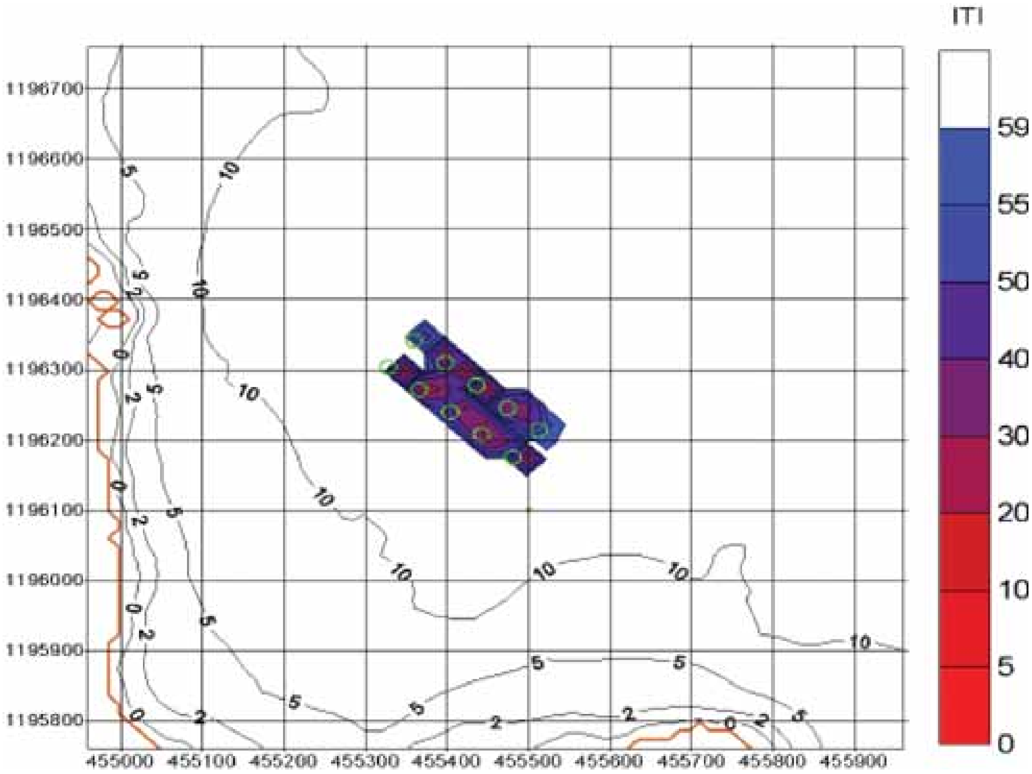
Figure 3.3 Current meter measurements at three salmon farms on maerl beds. Shetland (3.2m above the seabed June 2002), Orkney (distance above seabed not known, November 1998) and South Uist (4.5m above seabed, July 2000). The data represent the range of daily tidal current speed over a period of up to 3 weeks



3.4 Particle deposition modelling at Shetland using DEPOMOD

The DEPOMOD model output predicted that at feeding loads of 297 kg/pen/day (the input for three months prior to sampling) all of the material from the fish farm at Shetland would be resuspended from the 1km^2 grid, leaving no effect on the ITI. When the model was rerun using a feed input of 698 kg/pen/day (the maximum feed input of the previous two years) the model predicted that 99.2% of deposited material would be exported from the 1km^2 model grid, with a minimal effect on ITI directly under the fish farm cages (ITI scores corresponding to a 'changed' community). Figure 3.4 represents the model output from this second, high food-load scenario, predicting that more than 99% of food and faecal particulates would be exported from the model grid. It predicted that a minimal amount of material would remain within the grid and this would have a very limited effect on the trophic status of the benthic macrofauna, even directly underneath the cages.

Figure 3.4 DEPOMOD model predictions for feed input of 698 kg/pen/day at North Sandwick fish farm, Yell, Shetland



4 RESULTS: ANALYSES OF BIOLOGICAL DATA

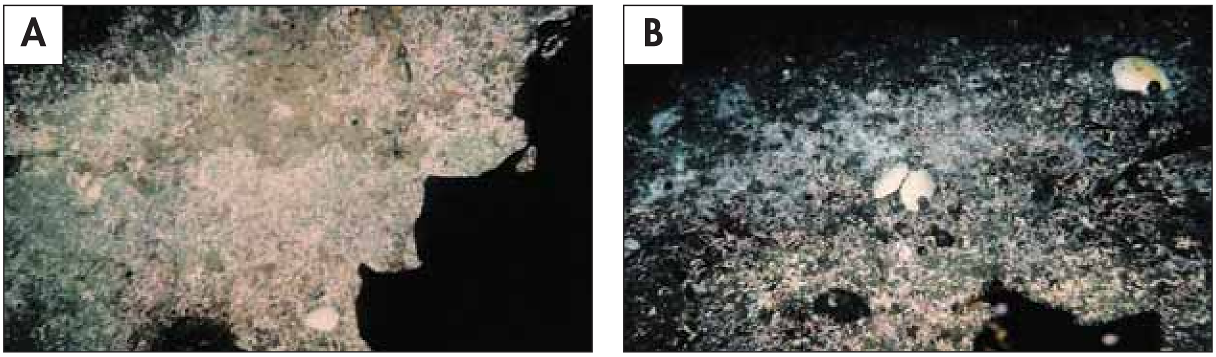
4.1 Historical monitoring data

As part of this study, reports of historical monitoring at each of the fish farms were obtained. Presented below is a summary of the findings from reports at each of the sites. These provide information on the historical use of the sites and reported effects of fish farming. They also provide an insight into the approaches and information that have been used for monitoring of each site in the past.

4.1.1 Historical monitoring data: Shetland

The North Sandwick site has been used intensively for fish farming for 14 years, with a detailed history of benthic monitoring, as summarised in Table 4.1. The cages have held up to 160 000 salmon (in 1996) and a biomass of up to 1150 t (in 2003). Photographs and C & R Diving Ltd reports from 1991–1996 show that the cages were first positioned on an area with 90% live maerl. Live maerl dropped to 30% over the next 4 years with intermittent records of waste feed, mats of *Beggiatoa* and areas of dead maerl (Figure 4.1). The cages were also moved onto sandy substrata at 13m depth (shallower than the other site records) in 1997 and repositioned on live maerl in 1998. The cages appear to have been moved again, because live maerl cover was back up to 80–90% in 1999 and 80% in 2000.

Figure 4.1 Seabed conditions next to cages at North Sandwick salmon farm on 20th June 1993; A) feed pellets and fish faeces on dead maerl (kelp obscures the right hand side of this picture), B) mats of *Beggiatoa* on a mixture of live and dead maerl. The site had been in use for two years at the time and was stocking 135,000 fish



Between 1991 and early 2002, monitoring comprised visual assessment of the seabed using photographs. Within this period, SEPA classed the site as 'Satisfactory', based upon the visual benthic reports. However, in late June 2002, the first infaunal assessment of the site was undertaken which revealed widespread change in the infaunal composition and the site was classed 'Unsatisfactory'. At the cage edge, polychaetes indicative of organic enrichment were present in extremely high densities (166 800m^{-2}) and the ITI score (2.89) showed that the site had been 'degraded' with a very low diversity index (0.67). There were few taxa compared with reference maerl sites in the area. The following year (2003) the caged biomass of salmon had been increased from 978 t to 1150 t but the site was classed as 'Satisfactory' because although effects on the seabed were observed, these lay within the extent of the allowable zone of effects (AZE). In particular enrichment polychaetes were not sampled in such high densities near the cage edge (4983m^{-2}) and the ITI score (30) indicated 'changed', rather than 'degraded' conditions. In 2003 the site was classified as 'borderline' on the basis of waste feed/faeces being seen from the cage edges out to 25m.

Table 4.1 SEPA site survey history for North Sandwick salmon farm, Shetland, 1991–2003. NB 'Fungus' denotes *Beggiatoa*.

Survey date	Survey type	Classification	Number or weight (t) of fish	Depth (m)	Notes
10/6/91	Visual	Satisfactory	100 000	13–14	90% live maerl no waste or 'fungus'
9/6/92	Visual	Satisfactory	105 000	15	70–90% live maerl no waste or 'fungus'
20/6/93	Visual	Satisfactory	135 000	14.7–15.3	60–90% live maerl waste feed and 'fungus' seen below cages
4/12/94	Visual	Satisfactory	63 000	15.6	30% live maerl mussels fallen from cages but no waste or 'fungus'
28/10/95	Visual	Satisfactory	70 000	16	50% live maerl no waste or 'fungus'
3/12/96	Visual	Satisfactory	160 000	15.2–15.5	60% live maerl no waste or 'fungus'
11/12/97	Visual	Satisfactory	44 000	13–13.5	Cage moved shallower. Sediment described as grey fine sand, no waste or 'fungus'
1/3/99	Visual	Satisfactory	330 t	14.5	Cage moved again. 80–90% live maerl No waste or 'fungus'
1/3/00	Visual	Satisfactory	120 t	14	80% live maerl no waste or 'fungus'
27/1/02	Visual	Satisfactory	Fallow	14.2–14.7	30–40% live maerl
14/6/02	Visual	Satisfactory	71 t	Not recorded	Site restocked in April 2002
27/6/02	Infaunal	Unsatisfactory	978 t	Not recorded	Widespread degradation in biodiversity and dominance by enrichment polychaetes
19/8/03	Infaunal	Satisfactory	1150 t	12–14	High densities of enrichment polychaetes to 25m from cages
5/9/03	Visual	Borderline	110 t	13.7–14.2	Sediment described as maerl and grey sand. Waste feed and faeces seen to 25m from cages

4.1.2 Historical monitoring data: Orkney

Monitoring conditions within the CoPA discharge consent to monitor Puldrite Bay require the consent holder to undertake visual surveys of the seabed. These survey reports are summarised in Table 4.2. In 1998 there was a maximum stocking density of 15kg m^{-3}. The cages had been moved around the site, from 12–18m water depth between 1998 and 2001 and shortly prior to surveys in 2003. The footprint of waste food/faeces had been up to 20m from the cages, but mats of *Beggiatoa* had not been recorded.

Table 4.2 SEPA site survey history for Puldrite Bay salmon farm, Orkney, 1992–2003.

Survey date	Survey type	Classification	Number or weight (t) of fish	Depth (m)	Notes
28/1/98	Visual	Satisfactory	Not recorded	Not recorded	Some waste to 20m from cages No 'fungus'
3/12/98	Visual	Satisfactory	70 000	12	Maerl bottom No waste or 'fungus'
18/1/01	Visual	Satisfactory	Not recorded	18	Brown sand with maerl Waste feed/faeces to 20m from cages, no 'fungus'

4.1.3 Historical monitoring data: South Uist

Monitoring reports for North Bay were obtained from 1999–2003. In June 2000, fauna close to the cages was dominated by opportunists (Nematodes, *Tubificoides benedii* and *Capitella capitata*) indicating organic enrichment. Diversity (when measured using the Shannon-Wiener index (H')) was moderately low 25m to the south of this site (H' = 1.51), increasing with distance to the north (H' = 2.05) up to H' = 4.81 at 25m north of the cages. Species richness and evenness also increased with distance from the salmon cages. The highest diversities (H' = 4.2–4.9) were recorded at the reference sites.

Grab surveys in 2002 showed live maerl cover increased from 5% on the north side of the cages, to more than 10% live at 50m from the cages and up to 80% 100m from the cages. Organic enrichment was evident and oligochaetes and polychaetes dominated (eg 2443 *T. benedii* in a 0.1m^2 grab at the cage edges) giving low ITI scores to 25m from the cages. Diversity index values increased with distance from the cages (H' = 3.13 at 0m, 3.52 at 25m, 3.56 at 50m, 4.52 at 100m) with the highest diversities found at the reference maerl sites (H' = 4.45 and 4.55). Waste feed, faeces or *Beggiatoa* mats were not seen so the site was classified as 'Satisfactory' (Table 4.3) but when infaunal surveys were carried out, the site was twice classified as 'borderline' based on changes to the species composition, with decreased diversity close to the cages.

Table 4.3 SEPA site survey history for North Bay salmon farm, South Uist, 1999–2003

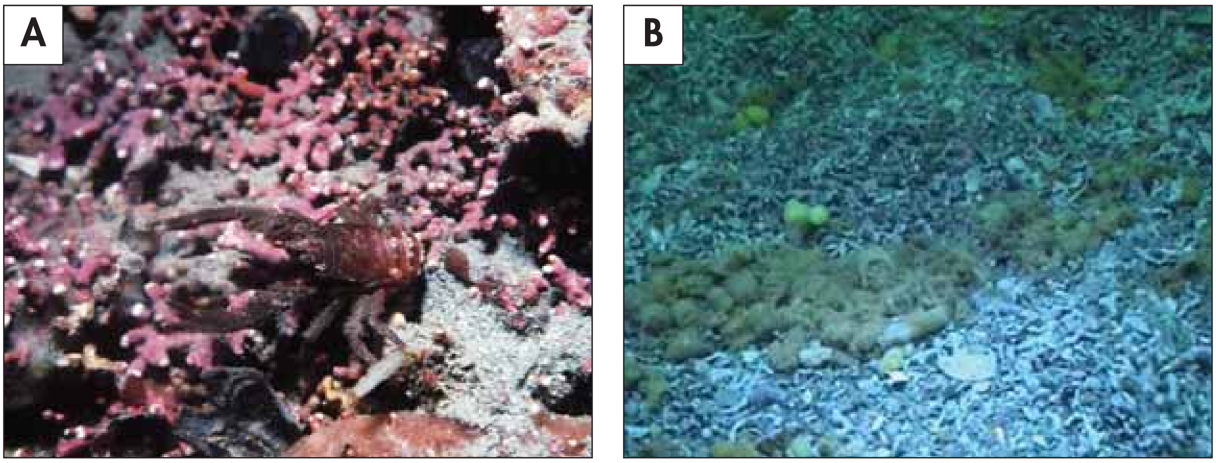
Survey date	Survey type	Classification	Number or weight (t) of fish	Depth (m)	Notes
18/11/99	Visual	Satisfactory	Not recorded	Not recorded	Maerl 'healthy' and no visual impact from cages
1/6/01	Infaunal	Borderline	Not recorded	Not recorded	High densities of enrichment polychaetes, low diversity and low ITI score out to 25m from cages
8/8/01	Visual	Satisfactory	Fallow	Not recorded	Shore crabs abundant No waste feed or fungus
13/5/02	Visual	Satisfactory	134 t	7	Live maerl to cage edge No evidence at all of fish cages impact
13/5/02	Infaunal	Borderline	134 t	7	Degraded infaunal communities to a distance of 25m. Site stocked in Nov 2001
9/6/03	Infaunal	Satisfactory	106 t	4–10	Slight enrichment at cage edge only

4.2 Assessment of visible effects on the benthos

At each site, a visual assessment of seabed was made by the divers recording features such as conspicuous epifauna, sediment colour, physical consistency, texture, presence of feed pellets and *Beggiatoa* mats. In this section the results from Shetland, Orkney and South Uist have been grouped since the visible effects of fish farms on the benthos were similar at each site. Transcripts of video transects from the diving surveys are provided in Appendix C and data from quadrat surveys are provided in Appendix D.

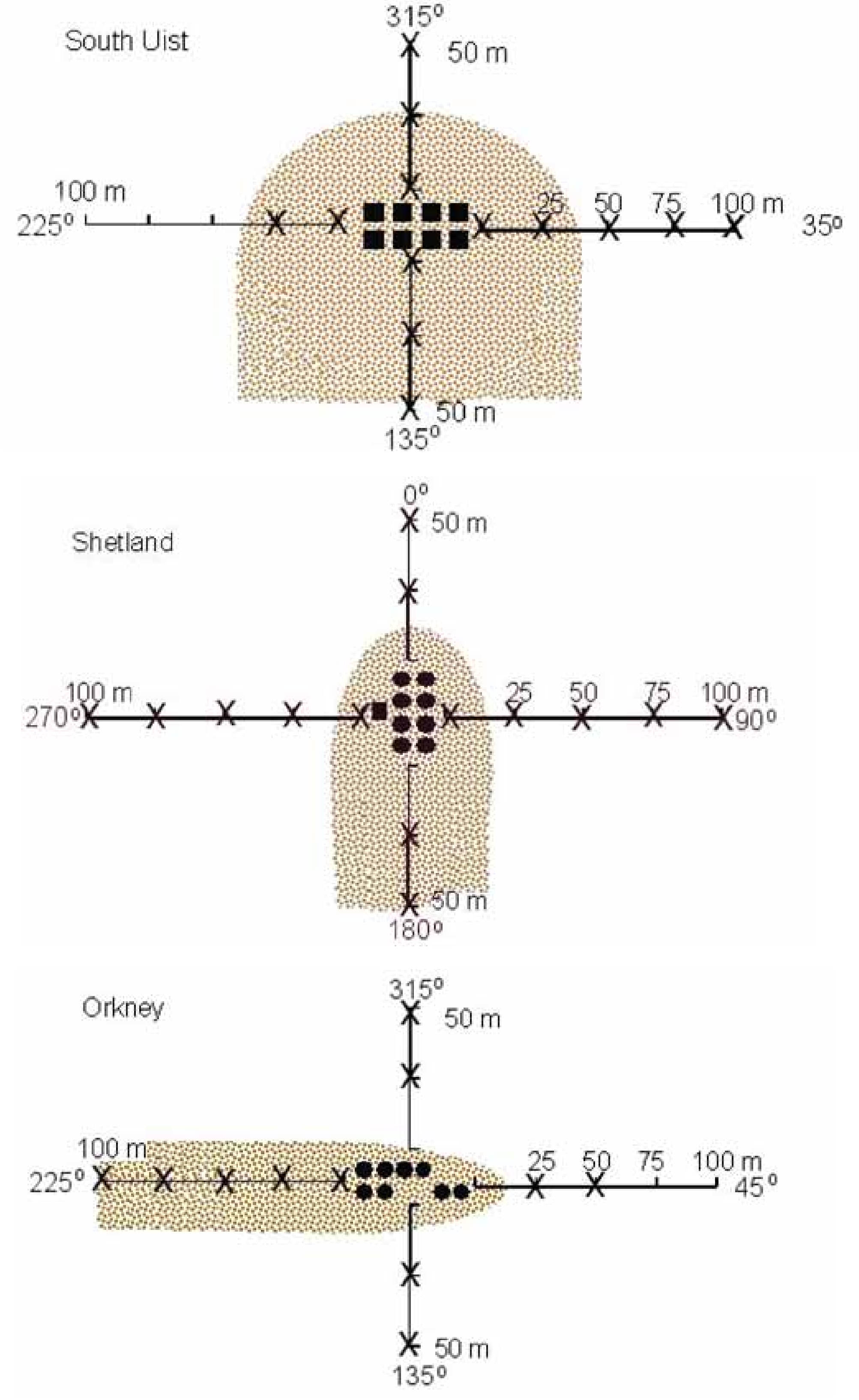
All reference sites (two in Shetland, two in Orkney and two in South Uist) showed no signs of organic waste and the habitats recorded were good examples of live maerl beds with abundant epiphytic growths of foliose red algae, small sponges, hydroids and bryozoans. At all of the reference sites, infaunal biomass appeared high, with visible siphons of large bivalves (eg *Dosinia exoleta, Tapes rhomboides*) and large holothurians (*Neopentadactyla mixta*) extending their feeding arms. Mobile fauna (Figure 4.2A) were abundant and diverse, particularly small gastropods, cryptic crustacea (eg amphipods, squat lobsters, small crabs) and juvenile ophiuroids.

Figure 4.2 A) Squat lobster *Galathea nexa* on live maerl *P. calcareum* at reference site 1 in South Uist, May 2003. Shells and patches of fine sediment increase the habitat heterogeneity. B) South Uist fish farm site (May 2003) with feed pellets on dead maerl 25m from the cages



At all three locations, the reference sites contrasted with conditions adjacent to the three fish farms. Obvious signs of organic enrichment were recorded near the cages at all three sites, such as uneaten fish feed, salmon faeces and bones, flocculent detritus and mats of *Beggiatoa,* which are indicative of anoxia. In South Uist, waste feed and fish faeces had accumulated in the troughs of sediment waves, in the pits dug by bioturbators (such as *C.pagurus* and the thallasinid shrimp *Upogebia deltaura*), and within the interlocking matrix of maerl thalli themselves (Figure 4.2B). Figure 4.3 shows the 'footprints' of gross organic enrichment observed at the three sites derived from *in situ* observations. At all three sites the footprint of effect is elongated and elliptical which is typical of locations where there are strong tidal streams. The largest area of visible organic enrichment was at the South Uist site, which had the slowest recorded current speeds. This set of cages had been in the same position for longest and this was confirmed by the amount of dead mussels shells (*Mytilus edulis*) that had fallen from the mooring ropes above. In South Uist and Shetland gross organic enrichment was recorded out to 50m. By contrast, in Orkney (where the smallest feed pellets were in use), feed pellets were found out to a distance of 100m although the footprint was far more elongated at this site than the other locations. It should be noted that these distances represent the outer survey points on those transects and therefore it is likely that the footprint extends beyond this distance.

Figure 4.3 Shaded areas show gross organic enrichment (feed pellets, fish faeces and/or *Beggiatoa* mats) recorded by divers (using video and quadrats) around salmon farms on maerl beds in South Uist, Shetland and Orkney in May/June 2003. Sampling sites and fish farm layouts are shown schematically. X = sampling station



The ecology of the "footprint" areas was observed to be markedly different from the reference sites. At all three sites, close to the cages the openings of polychaete burrows were more common, but there were few epiphytes and epifauna. Close to the cages there were also no visible bivalve siphons, an absence of large filter-feeders (eg *Sabella pavonina*, *Pecten maximus*, *N. mixta*) and a lowered diversity and abundance of cryptic fauna such as small crustaceans and gastropods.

With increasing distance from the fish farm cages, the effects of the farms became less noticeable at all sites. For instance in South Uist no epiphytic algae were seen within 10m of the cages. Further from the cages both abundance and diversity of algae (eg *Halarachnion ligulatum, Dudresnaya verticillata, Gracilaria gracilis, Laminaria* sporelings) increased with distance with the filamentous red alga *Trailliella intricata* common on maerl from 50m outwards. Large sessile organisms were absent within 10m of the cages but organisms such as the deep-burrowing anemone *Cerianthus lloydii* and the infaunal holothurian *N. mixta* became increasingly common in the maerl with increasing distance from the farm, although reference site conditions were not seen, even at 100m from the cages. At the most visibly impacted site, South Uist, the anemone *Metridium senile* appeared to be resilient to the presence of the fish farm being common on ropes and rocks emerging from the mat of *Beggiatoa* within 25m of the cage edge.

At all sites, organic waste had caused clear shifts in the trophic status of the maerl habitats, attracting scavenging macrobenthos in very high densities (except in anoxic areas) (Figure 4.4A). Table 4.4 provides *in situ* estimates of scavenging macrobenthos densities adjacent to the farms and at reference sites. The suite of scavenging species (the whelk *Buccinum undatum*, the crabs *C. pagurus, Carcinus maenus, Liocarcinus* sp., *L. depurator, L. corrugatus, Necora puber, Pagurus bernhardus,* Paguridae indet. and the starfish *Asterias rubens*) was similar at each set of salmon cages and 10–100 times more abundant near to the cages than at the reference sites. However, very close to the cages many of these species were dead (Figure 4.4B). Dead macrobenthos observed around the cages included the sea urchin *Echinus esculentus*, the tunicate *Ciona intestinalis* and an abundance of dead swimming crabs (mostly *C. maenus* and some *N. puber*). Fish abundances were not quantified, as their activities were affected by the divers, although the painted goby *Pomatoschistus pictus*, plaice *Pleuronectes platessa* and juvenile gadoids were seen feeding on fish farm waste.

Figure 4.4 A) *Carcinus maenus* feeding on pellets SW of South Uist fish farm, note that all the maerl was dead and was grey in colour. B) *Beggiatoa* and flocculent particulate organic matter smothering dead maerl adjacent to South Uist salmon farm cages, May 2003. Dead crabs, such as this *C. maenus*, were present on the maerl bed out to a distance of 25m SE of the cages

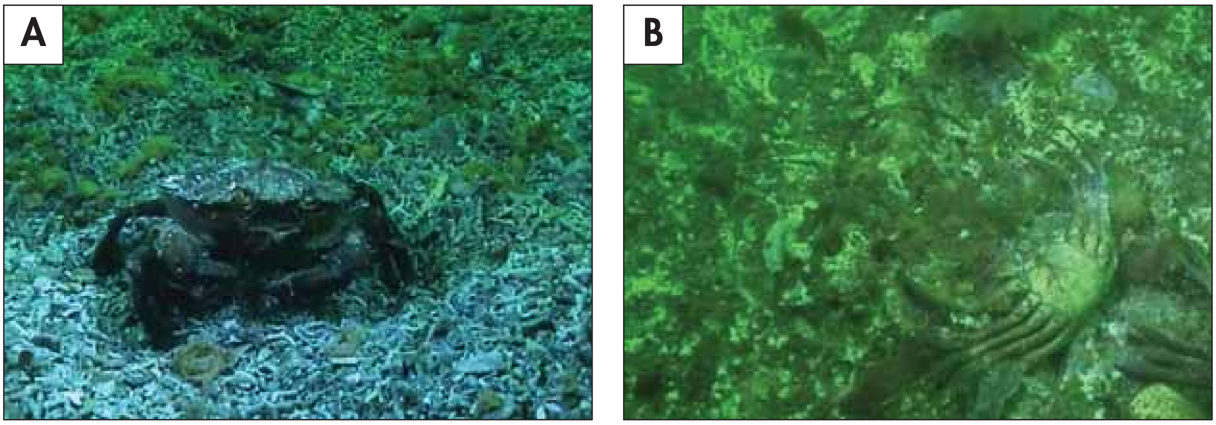


Table 4.4 Abundances of scavengers from *in situ* estimates classified in accordance with the MNCR SACFOR abundance scale (Common =1–9/1m^2, Frequent =1–9/10m^2, Occasional =1–9/100m^2, Rare =1–9/1000m^2, '–'= not seen). '*' shows 10–100 times higher abundances near cages

Taxa	**Shetland**		**Orkney**		**South Uist**	
	Ref Site	**Near cage**	**Ref Site**	**Near cage**	**Ref Site**	**Near cage**
Cancer pagurus	Occasional	Frequent*	Rare	Rare	Occasional	Rare
Carcinus maenus	Rare	–	–	Occasional*	Rare	Frequent*
Liocarcinus spp.	Occasional	Frequent*	Occasional	Frequent*	Occasional	Frequent*
Necora puber	Rare	Occasional*	Rare	Occasional*	Rare	Occasional*
Paguridae	Occasional	Frequent*	Occasional	Frequent*	Occasional	Frequent*
Asterias rubens	Rare	Rare	Rare	Occasional*	Occasional	Common*
Buccinum undatum	Rare	Occasional*	Occasional	–	Rare	Occasional*

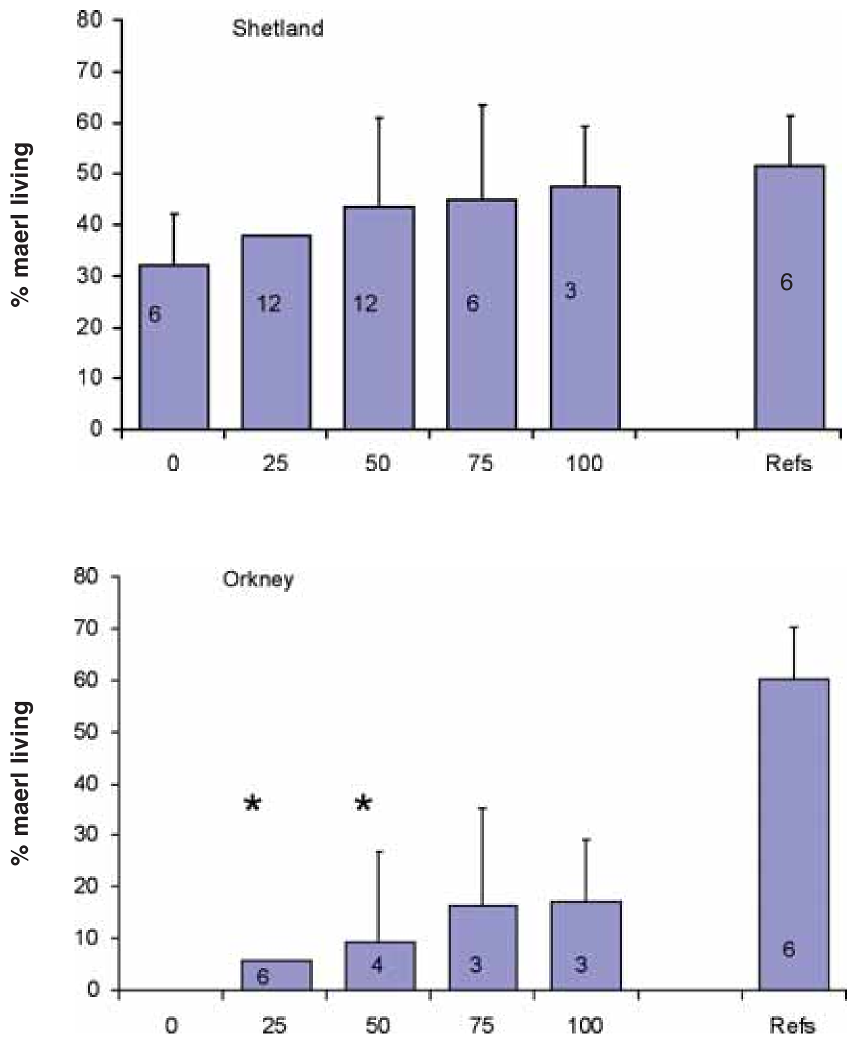
In addition to effects through organic deposition, the fish farms were observed to have physical impacts on the benthos at all three sites. These included crushing of maerl under chains that swung around the mooring gear, shading, and smothering by nets, ropes and mussel shells (*M.edulis*) that had fallen from the fish farm structures.

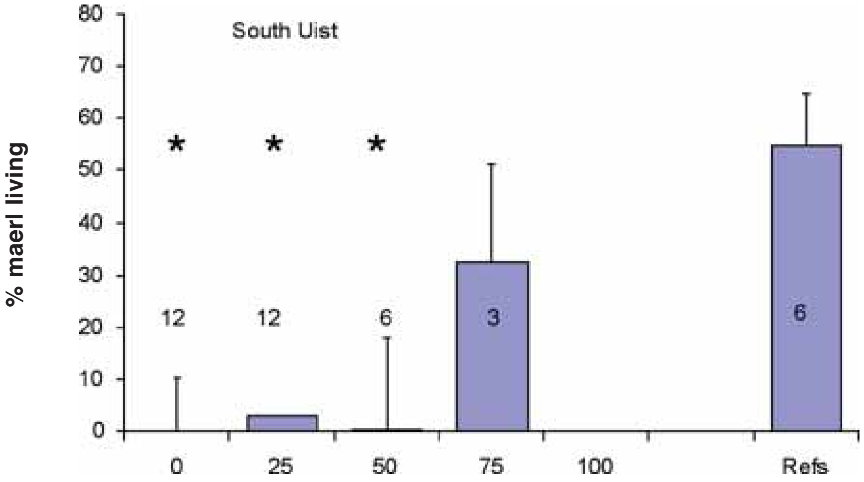
4.3 Assessment of live versus dead maerl cover

In situ observations provided a more detailed assessment of live versus dead maerl cover compared to analysis of photographs, as divers were able to survey wide areas by eye and search through seabed material manually. They were able to locate live maerl when it was heavily epiphytised by foliose and filamentous seaweeds at the reference sites, or locate dead maerl when it was covered in a layer of particulate matter near to cages. This method had the advantage of providing a rapid assessment, but provided no permanent visual record for archive purposes. *In situ* stills photographs of 50cm x 50cm quadrats did not provide the quality of images needed to subsequently assess the abundance of live and dead maerl within quadrats, since individual maerl branches were usually less than 5mm wide and difficult to see in the pictures. Even when four still photographs were taken, one of each quarter of the quadrat, it was difficult to assess the relative amounts of live and dead maerl. Nevertheless, a compact disc (CD) of the replicate quadrat stills photographs taken as part of this project is lodged with SNH. Video filming of 10cm x 10cm squares within 50 x 50cm quadrats did work well, however, providing a permanent record of each quadrat, although analysis of the video proved highly time-consuming and less accurate than *in situ* records because epiphytes or particulate matter often obscured the presence of maerl.

The data and accompanying notes from *in situ* observations are provided in Appendix D and summarised in Figure 4.5. Each of the pairs of reference maerl sites in Shetland, Orkney and South Uist were characterised by a high cover of maerl of which a high percentage was live (50–60% of maerl present was alive), although it should be noted that the reference sites were selected as they were good examples of live maerl beds in the area. All of the reference sites also had patches of dead maerl, which is normal in areas where the surface material is shifted by water movement or bioturbating organisms. The proportion of maerl that was live was consistently lower on the transects around the fish farms than at the reference sites. Live maerl was found near to the cages in Shetland, but this had a mottled appearance with patches of pigment-loss over the surface of the thalli. Maerl around the Shetland fish farm was megarippled, suggesting that live maerl may be transported into the area during rough weather. The Orkney data show a large drop in the proportion of maerl that was live between the reference sites and the fish farm transects, but this needs to be interpreted with caution since the cages had recently been moved onto an area of seabed where there was only scattered maerl on a predominantly sandy substratum. Fish farm deposition had its most visible effect on live maerl cover at the South Uist site, where a thick layer of silt was present on the maerl downstream (south) of the cages. At this site, around the cages the maerl either had a mottled pigmentation and was clogged with silt or was dead and grey in colour. Statistically significant reductions in live maerl cover were recorded in quadrats up to 50m from the cages in South Uist, with live maerl exhibiting the same mottled appearance as thalli from the Shetland and Orkney sites.

Figure 4.5 Mean percentage of maerl present in replicate 0.5 x 0.5m^2 quadrats that was live taken on reference maerl beds and on transects at 0–100m from salmon cages in Shetland, Orkney and South Uist. Error bars are +Standard Deviation with the number of replicates shown on each bar, * show significantly lower % live maerl than reference sites. NB. The 100m site at South Uist consisted of bedrock with kelp

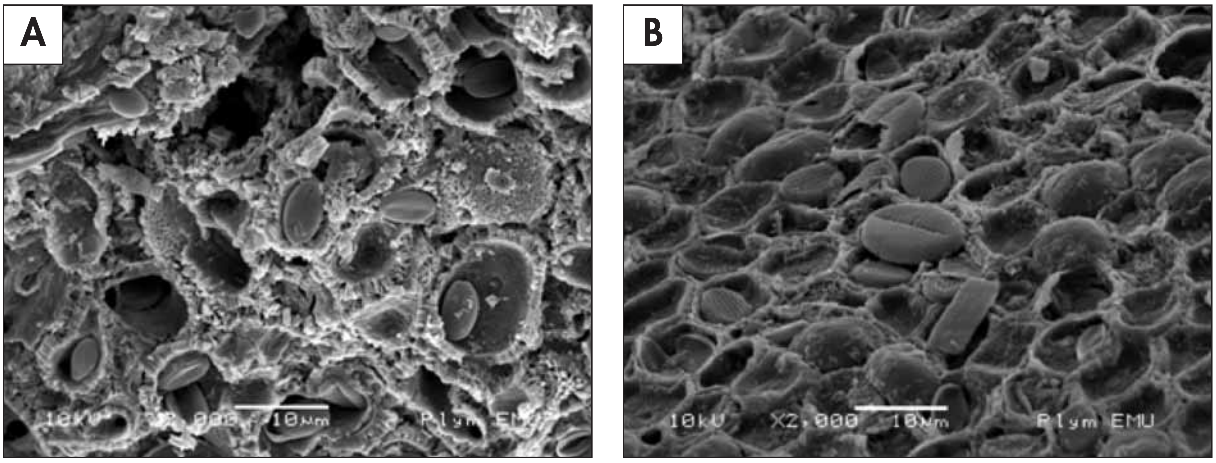




4.4 Maerl damage: Scanning electron microscopy

Microscopic examination of maerl samples collected from stations next to the cages, 50m from the cages and at the reference sites showed that at all sites the maerl species present was *P. calcareum*. In addition to determining the taxonomy, the microscopic examination of the samples also provided an indication of the health of the maerl thalli. Many of the specimens collected near the salmon cages had an unhealthy mottled appearance, due to loss of phycobilin pigmentation, and showed erosion of the epithallus. In contrast, most of the live maerl collected from 50m from the salmon cages, and all of the live maerl collected at the reference sites had a healthy, uniformly pigmented appearance (not mottled) and had intact epithallial cells (Figure 4.6).

Figure 4.6 A) Scanning electron micrographs of impacted maerl *P. calcareum* with eroded epithallial cell walls. B) unimpacted maerl with epithallus intact (both have epiphytic diatoms attached)



4.5 Infaunal analyses

Infaunal analyses confirmed that Scottish maerl beds can be highly diverse benthic habitats, with the polychaete and small crustacean (ostracods, mysids, amphipods, isopods, tanaids, cumaceans and small decapods) components of the fauna standing-out as being particularly rich. A wide range of species were found that would normally characterise a range of substrata, from soft muds (eg *Eusirus longipes,* *Westwoodilla caecula*), sands (eg *Corophium crassicorne, Urothoe elegans, Philine scabra, Thyasira flexuosa, Ophiura ophiura*) and gravels (eg *Owenia fusiformis, Polygordius lacteus, Monoculodes carinatus, Ceradocus semiserratus, Gibbula tumida, Echinocyamus pusillus*) to shell and hard substrata (eg *Pomatoceros lamarki, Leptochitona asellus, Tectura virginea, Pododesmus patelliformis*). Provided below is an account of the infaunal communities recorded at each site. The effect of the fish farms on infaunal communities has been determined by analysing how both the univariate characteristics (ie number of taxa, diversity etc.) and multivariate statistics varied at the site. An explanation of the statistical parameters used is provided in Box 5.1 and the full dataset is presented in Appendix E.

Box 5.1 Explanation of statistical parameters used to describe communities

Evenness (or Equitability): This is a measure of how evenly individuals are distributed among the different species.

Infaunal Trophic Index (ITI): The Infaunal Trophic Index (ITI) is a biotic index, which has been developed by the Water Research Centre and varies between 0 and 100. It relies on the assessment of the changes in the feeding (trophic) mode of benthic organisms in areas subject to increasing organic enrichment. Details of the index and its use can be found in WRc (Codling & Ashley, 1992). SEPA (2003) adopts the following classification to interpret ITI values with regard to benthic communities around fish farm sites:

- 60 to 100 value: Community is 'Normal';
- 30 to 60 value: Community is 'Changed';
- less than 30 value: Community is 'Degraded'.

Number of individuals (N): The abundance or number of individuals in a population.

Number of species (S): The number of species in a sample or group of samples.

Pielou's evenness index (J'): This is a measure of evenness or equitability in a community, which is defined as the extent to which the individuals are equally portioned among all species.

Shannon-Wiener's diversity index (H'): This is the measure of the diversity of a community which incorporates both species richness and equitability components. The higher the Shannon-Weiner value the more diverse the community.

Simpson's dominance index (D): This is essentially the reverse of evenness. If a sample has a high dominance value it is highly dominated by one species.

Standard deviation: A measure of the average amount by which each observation in a series of observations differs from the mean.

4.5.1 Shetland infaunal analyses

Table 4.5 presents summary univariate statistics for the infaunal communities from Shetland. The total numbers of infaunal taxa found in replicate (n=5) cores close to the cages (72–75 taxa) were lower than the total numbers of taxa sampled in replicate (n=5) cores at the reference sites (80–139 taxa). Similarly, the mean number of taxa per core increased with distance from the cages from 28 up to 52 at the reference sites (Figure 4.7). All measures of community structure showed marked effects with low dominance, high evenness and high diversity at the reference sites *cf.* higher dominance, lower evenness and lower diversity close to the cages. ITI scores were low (<30) up to 75m from the cages indicating a 'degraded' benthic community. The ITI scores were lowest (2.89) at the edges of cages and increased with distance from the cages up to scores of around 60 at 100m from the cages. Multivariate analysis using the Plymouth Routines in Multivariate Ecological Research (PRIMER) software (Clarke & Warwick, 2001) has been used to determine how the community differs within each study area, taking into account the species identity. The similarity of the samples from each sampling station, as represented by the Bray-Curtis similarity index are presented in Figure 4.8. This shows that there is no clear trend in the similarity of the samples and no clear groups of samples can be distinguished. The reference sites are relatively similar and the sites closest to the cages (ie those 0–25m on the transects) cluster relatively closely together.

K-dominance curves have been plotted to show the percentage representation of the population by different species. Where infaunal marine communities are exposed to a stress gradient (whether natural or anthropogenic) some species within the community typically disappear and are replaced in the population by large numbers of those (resistant) species that are capable of survival and growth. Figure 4.9 presents the *K*-dominance curve for the Shetland data. It clearly shows that the samples closest to the cages show the highest dominance by one or two species, which is typical of 'stressed communities'.

Table 4.5 Summary statistics for 1mm sieved 0.01m^2 replicate (n = 5) infaunal core samples collected in Shetland at reference maerl sites (ref1 and ref2) and on transects out from a salmon farm. Statistics show the total number of species (S) and total number of individuals (N) in all five cores together with Simpson's dominance index (D), Pielou's evenness index (J'), Shannon-Wiener's diversity index (H') and Infaunal Trophic Index (ITI) score. (See Box 6.1 for an explanation of these parameters)

	S	N	D	J'	H'($\log_e$)	ITI score
T1–0m	72	9301	7.769857	0.156482	0.669222	2.89
T1–25m	85	2425	10.77809	0.417551	1.855033	12.07
T1–50m	117	2419	14.88877	0.547016	2.604984	23.38
T1–75m	75	1007	10.70179	0.608699	2.628049	25.32
T1–100m	32	177	5.989008	0.76739	2.659569	61.96
T2–0m	75	1798	9.873999	0.495895	2.141022	15.49
T2–25m	67	343	11.30576	0.751358	3.159231	47.07
T2–50m	76	403	12.50222	0.786423	3.405789	53.29
T2–75m	96	438	15.6193	0.814811	3.71908	51.82
T2–100m	129	1296	17.85954	0.769901	3.741575	60.57
T3–25m	102	6828	11.43985	0.359003	1.660378	8.41
T3–50m	41	1958	5.277268	0.38807	1.441126	5.38
T4–25m	71	2205	9.092701	0.39319	1.676042	8.31
T4–50m	77	1245	10.66384	0.445968	1.9372	13.94
ref1	139	1953	18.21272	0.75355	3.718372	64.98
ref2	80	550	12.51997	0.781396	3.424098	58.26

Figure 4.7 Mean number of taxa recorded in replicate 0.01m^2 core samples taken on reference maerl beds and on transects at 0–100m from salmon cages in Shetland. Error bars are +Standard Deviation with the number of replicates shown

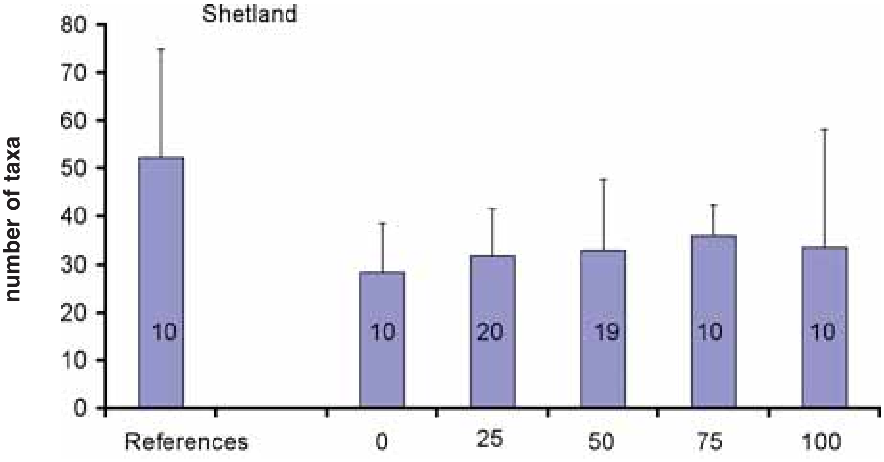


Figure 4.8 Multi-dimensional scaling (MDS) plot of Bray-Curtis similarity indices for all data from Shetland (using log X+1 transformation)

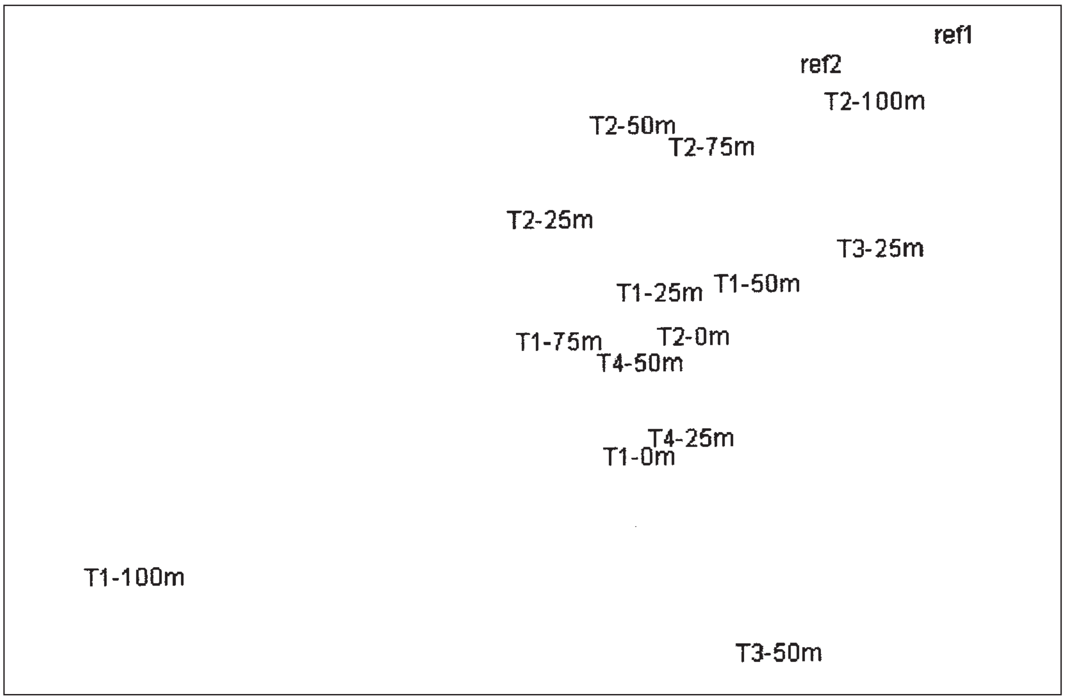
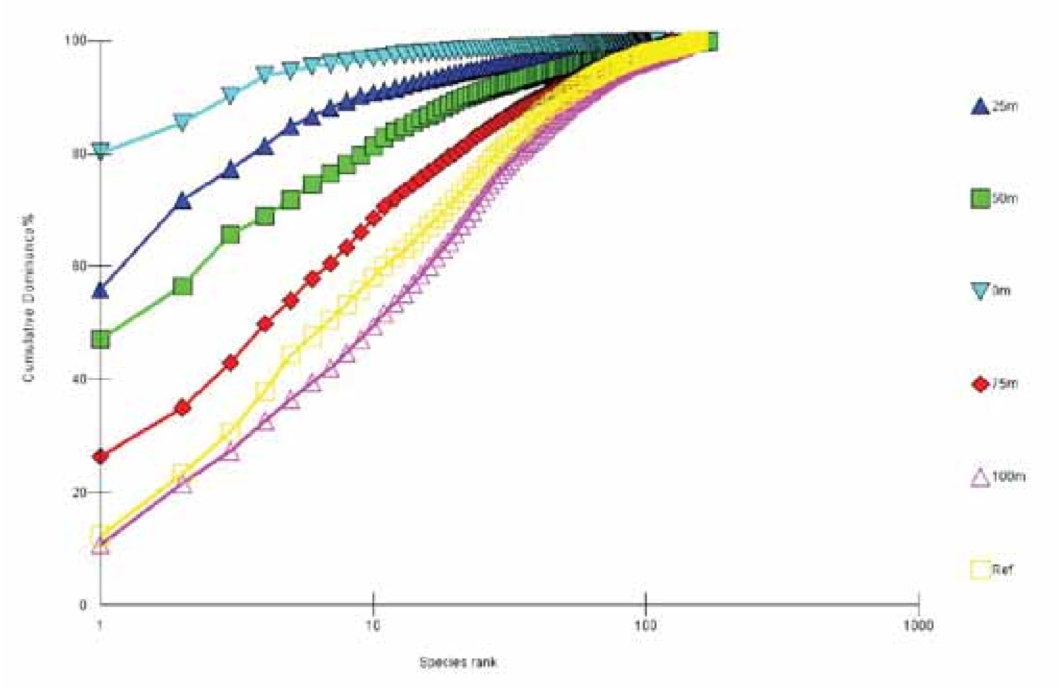


Figure 4.9 K-Dominance curves for infaunal data from 1mm sieved 0.01m^2 infaunal core samples collected in Shetland at reference maerl sites and on transects out from a salmon farm



A number of maerl-dwelling taxa were found to be abundant at reference sites, but had marked reductions in population density close to the Shetland fish farm. Examples include ostracods, isopods (Gnathidae indet., *Eurydice* juv. Indet., *Cymodoce* sp., *Janira maculosa*, *Microcharon harrisi*, *Munna* sp., *Paramunna bilobata*, *Eurycope* sp., *Idotea granularis*), tanaids (*Leptognathia breviremis, L. paramanca, Pseudoparatanais batei, Tanaiopsis graciloides, Typhlotanais microcheles*) and cumaceans (*Vaunthompsonia cristata, Cumella pygmaea, Nannastacus brevicaudatus, N. unguiculatus*) (Table 4.6).

Table 4.6 Mean numbers (± Standard Deviation) of ostracods, isopods, tanaids and cumaceans recorded in replicate 0.01m^2 core samples taken on reference maerl beds and on transects at 0–100m from salmon cages in Shetland. Note their paucity near cage sites

Taxa	**0m (n=10)**	**25m (n=20)**	**50m (n=19)**	**75m (n=10)**	**100m (n=10)**	**Ref sites (n=10)**
Ostracods	9.5 ± 10.2	11 ± 14.4	12.6 ± 16.2	12.6 ± 11.5	19.5 ± 20.6	32.5 ± 27.5
Isopods	<1	4.2 ± 8.2	<1	<1	3.2 ± 4.8	6.6 ± 6.1
Tanaids	0	<1	<1	<1	5.1 ± 6.9	6 ± 6.1
Cumaceans	<1	<1	1.8 ± 2.1	1.5 ± 1.2	13.4 ± 21.3	19 ± 17.2

Although the abundances of most species were lower near to the fish farm cages, a few species are well adapted to utilise fish farm waste as a food source and these occurred in increased abundances. Examples of opportunists present in high numbers close to the cages include the polychaete *C.capitata* (a well-known indicator of organic enrichment), the scavenger *Ophryotrocha hartmanni* (often found feeding on organic matter in marine aquaria) and *Socarnes erythrophthalmus* a voracious scavenging amphipod (see Table 4.7). Due to the abundance of these species, the mean number of individuals per core was higher close to the cages (>1000 individuals per core) decreasing to about 250 individuals per core at 75m, 100m and the reference sites (Figure 4.10).

Figure 4.10 Mean number of individuals recorded in replicate 0.01m^2 core samples taken on reference maerl beds and on transects at 0–100m from salmon cages in Shetland. Error bars are +Standard Deviation with the number of replicates shown

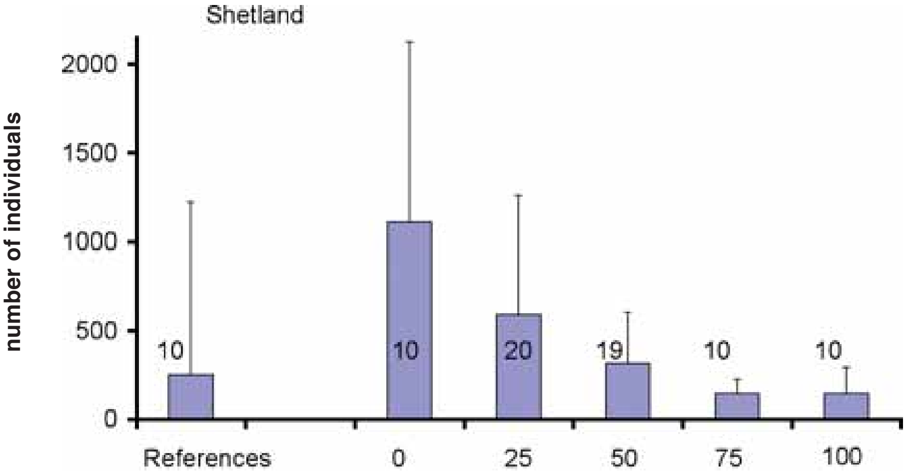


Table 4.7 Mean numbers of opportunists recorded in replicate 0.01m^2 core samples (n=10–20) taken on reference maerl beds and on transects at 0–100m from salmon cages in Shetland. Note their high abundances near cages

Species	0m	25m	50m	75m	100m	Ref sites
Capitella capitata	40	41	43	23	7	<1
Ophryotrocha hartmanni	890	330	189	54	2	<1
Socarnes erythrophthalmus	58	98	35	6	40	23

At the Shetland site, the samples were also sieved using a 0.5mm mesh in order to provide a comparison between using a 0.5mm and 1mm mesh sizes. When the samples were sieved using a 0.5mm mesh, 21 additional taxa were recorded which had not been recorded when using the 1mm mesh. However, given that a total of 314 different taxa had been recorded from the samples at Shetland, this is a relatively small number of additional taxa and it is therefore considered that the use of a 1mm mesh was sufficient for characterising the samples for the purposes of this assessment.

In summary, core sampling revealed that the reference sites had large numbers of species occurring at low densities whereas the samples on the fish farm transects had reductions in species diversity and an increased dominance of a few species. The trophic status of the maerl beds was radically altered close to the cages, with very high abundances of opportunistic species (eg *C.capitata*), which are adapted to organic enrichment.

4.5.2 Orkney infaunal analyses

Core samples collected from around the fish farm cages in Orkney had a much impoverished infauna (low diversity and abundances) compared with the reference sites. Table 4.8 shows summary community statistics for Orkney. The total numbers of infaunal taxa found in replicate (n=5) cores close to the cages (34 taxa) were considerably lower than the total numbers of taxa recorded in replicate (n=5) cores at the reference sites (157–164 taxa). The reference sites were much more diverse (with means of *circa* 78 taxa per core) than those from around the fish farm (with 15–40 taxa per core) (Figure 4.11).

As in Shetland, many groups were significantly more diverse at the reference sites than close to the salmon cages. For example, the isopods Gnathidae indet., *Eurydice inermis, Cymodoce* sp., *J. maculosa, Munna* sp., *P. bilobata, Pleurogonium spinoissimum, Idotea* sp. and *Arcturella damnoniensis* were all present in core samples from the reference sites but no isopods were found close to the cages. This was also the case for tanaids (*L. breviremis, L. paramanca, P. batei, T. graciloides and T. microcheles*) and cumaceans (*V. cristata, Bodotria scorpioides*, *C. pygmaea, N. brevicaudatus, N. unguiculatus, Pseudocuma similes* and *Diastylis rugosa*). Quantitative data for these crustacean groups show that they were far more abundant at the reference sites than around the fish farm cages (Table 4.9).

Table 4.8 Summary statistics for 1mm sieved 0.01m^2 replicate (n = 5) infaunal core samples collected in Orkney at reference maerl sites (ref1 and ref2) and on transects out from a salmon farm. Statistics show number of species (S) number of individuals (N), Simpson's dominance index (D), Pielou's evenness index (J'), Shannon-Wiener's diversity index (H') and Infaunal Trophic Index (ITI) scores

	S	N	D	J'	H' (log$_e$)	ITI
T1–25m	119	1469	0.901133	0.706566	3.376766	68.44
T1–50m	99	764	0.943276	0.767925	3.528708	63.78
T2–0m	34	173	0.903683	0.796213	2.807733	38.54
T2–25m	46	255	0.937996	0.836867	3.204062	43.58
T2–50m	58	304	0.943178	0.810834	3.292347	52.98
T2–75m	55	419	0.900252	0.73932	2.962701	59.26
T2–100m	86	1133	0.835687	0.64317	2.864904	57.69
T3–25m	68	395	0.945512	0.797291	3.364174	72.48
T3–50m	81	294	0.940819	0.818611	3.597345	69.93
T4–25m	130	2124	0.802297	0.590929	2.876365	79.76
T4–50m	121	1767	0.858881	0.64144	3.076212	76.11
Ref1	157	5619	0.901221	0.617768	3.123587	76.16
Ref2	164	2523	0.92082	0.6921	3.529619	77.82

Figure 4.11 Mean number of taxa recorded in replicate 0.01m^2 core samples taken on reference maerl beds and on transects at 0–100m from salmon cages in Orkney. Error bars are +Standard Deviation with the number of replicates shown

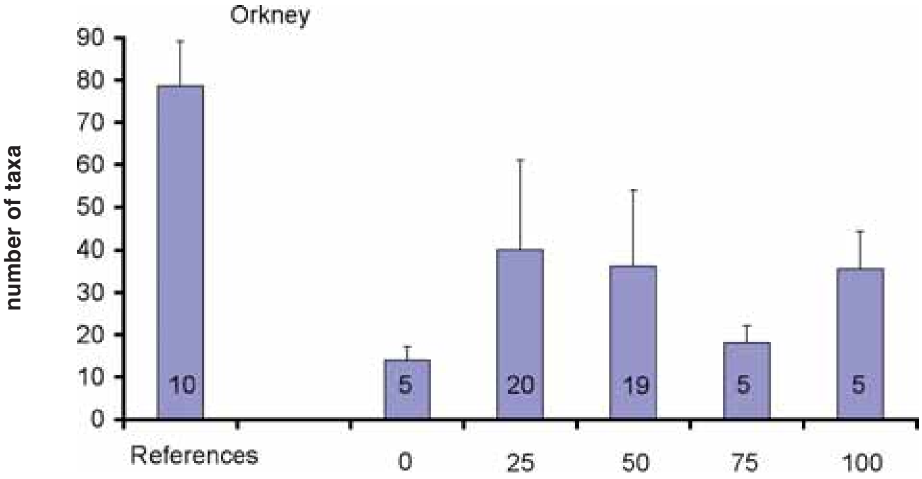
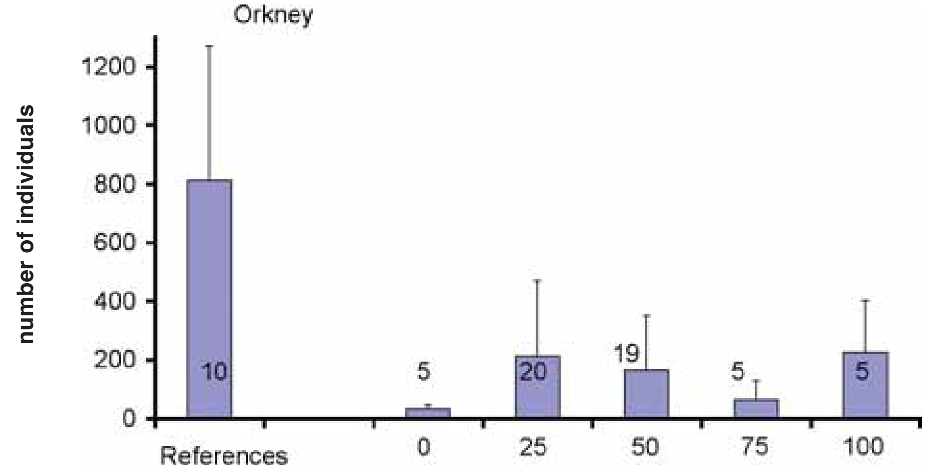


Table 4.9 Mean number (± Standard Deviation) of individual ostracods, isopods, tanaids and cumaceans recorded in replicate 0.01m^2 core samples taken on reference maerl beds and on transects at 0–100m from salmon cages in Orkney. Note their paucity near cages

Taxa	0m (n=5)	25m (n=20)	50m (n=19)	75m (n=5)	100m (n=5)	Ref sites (n=10)
Ostracods	<1	3.6 ± 3.3	3 ± 3.6	0	<1	21 ± 15.9
Isopods	0	4 ± 6.6	3 ± 4.6	<1	<1	21 ± 13.7
Tanaids	0	<1	1.2 ± 2.2	0	<1	9 ± 7.7
Cumaceans	0	2.3 ± 3.9	3 ± 7.1	0	16 ± 1.5	18 ± 15.2

As well as lower overall diversity, far lower abundances of individual taxa were recorded in the vicinity of Orkney salmon cages than at the reference sites (Figure 4.12). It is noteworthy that although species indicative of organic enrichment were present around the cages (eg *C. capitata*), they were not nearly so abundant as at the Shetland site which is why statistical descriptors of community structure (Table 4.8) do not show the same degree of effect as those recorded in Shetland.

Figure 4.12 Mean number of individuals recorded in replicate 0.01m^2 core samples taken on reference maerl beds and on transects at 0–100m from salmon cages in Orkney. Error bars are +Standard Deviation with the number of replicates shown



The similarity of the samples from the different sampling stations has been compared using the Bray-Curtis similarity index (Figure 4.13 and Figure 4.14). These show that two distinct groups of samples can be seen. The samples from the reference sites, transect 1 and transect 4 cluster together, as do the samples from transects 2 and 3. Compared to Shetland there are less clear trends in community structure with increasing distances from the cages on the transects. For example, as shown in Figure 4.11, there is no clear increase in the number of taxa with increasing distance from the cages. Similarly, there is no clear trend in the dominance of the samples as shown by the K-dominance curve (Figure 4.15). This is echoed by the Figures 4.13 and 4.14 which show that the samples from each transect are more similar to each other than the samples from different distances.

The overall effect of the fish farms on the infaunal community appears to less severe than at Shetland when measured using the ITI scores. For example at Shetland, most of the samples close to the cages had ITI scores of less than 30 meaning that they are classified as 'degraded'. In contrast, all samples from Orkney had scores of higher than 30 with many higher than 60, which would be classified as 'changed' and 'normal' respectively.

Figure 4.13 Dendrogram of Bray-Curtis similarity indices of infauna from Orkney using log X+1 transformation

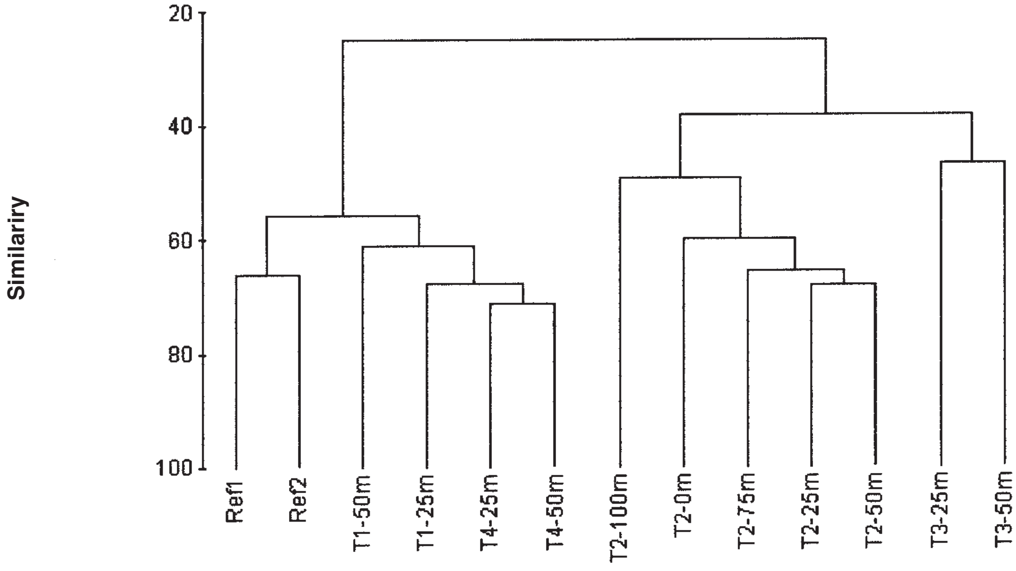


Figure 4.14 Multi-dimensional scaling plot of Bray-Curtis similarity indices of infauna from Orkney using log X+1 transformation

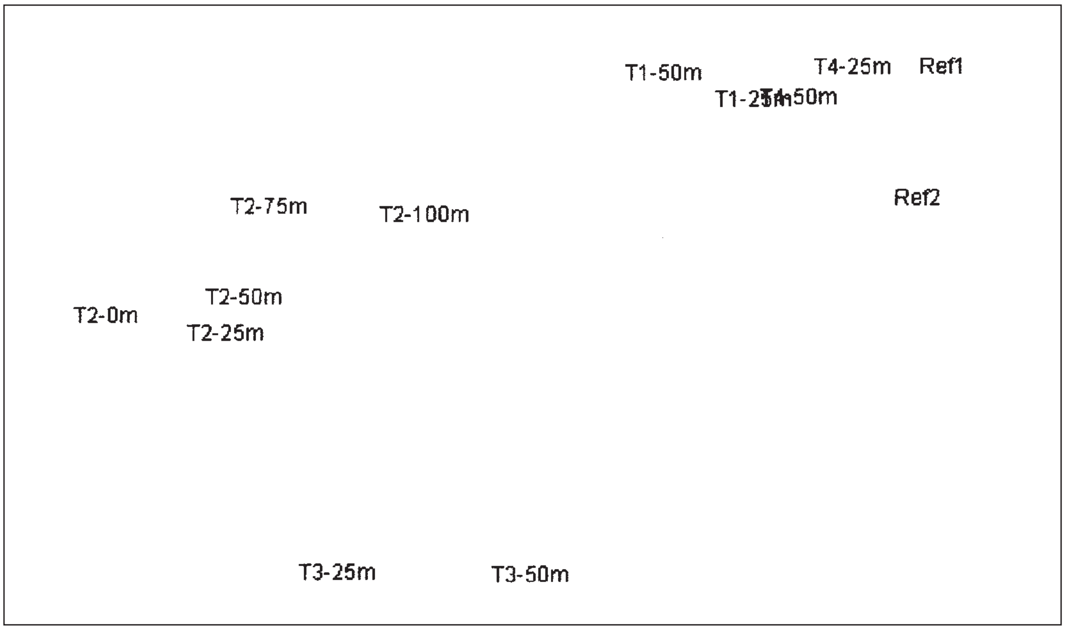
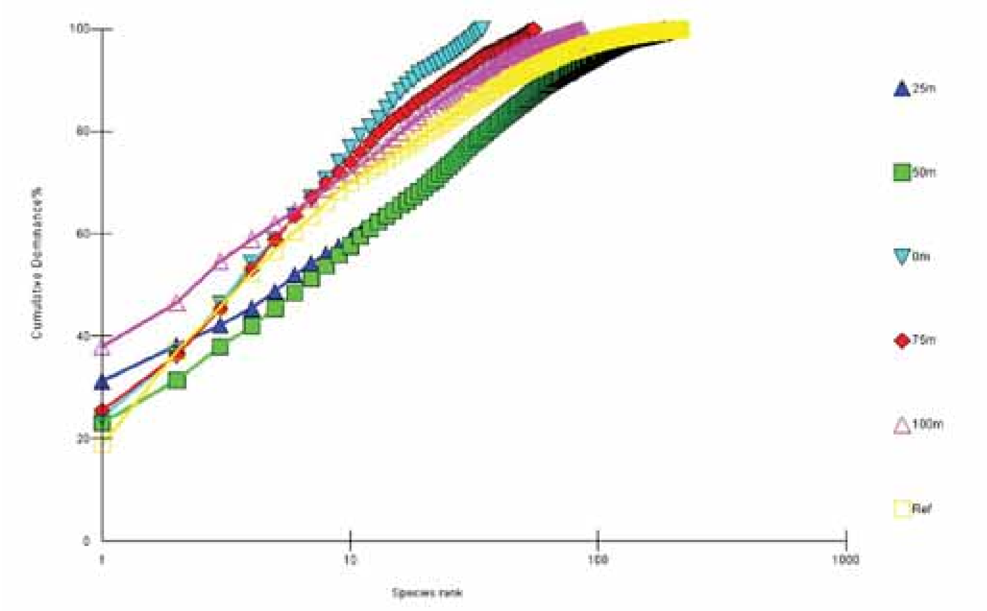


Figure 4.15 K-Dominance curves for infaunal data from 1mm sieved 0.01m^2 infaunal core samples collected in Orkney at reference maerl sites and on transects out from a salmon farm



4.5.3 South Uist infaunal analyses

Fewer infaunal data are available for South Uist, because samples were collected by grab from only three stations near the fish farm cages and there were fewer replicates. Summary statistics for the samples are presented in Table 4.10. The data indicate that north of the fish farm there was no significant reduction in infaunal diversity (Figure 4.16) compared to the reference stations. The similarity of the samples has been compared using the Bray-Curtis similarity index (Figure 4.18). This shows that samples from the transect stations are more similar to each other than the samples from the reference sites.

Trophic status and community structure close to the cage edge was indicative of organic enrichment, with high densities of species such as *C. capitata, T. benedii* (an oligochaete tolerant of low oxygen and high sulphur conditions) and *Socarnes erythrophthalmus* (Table 4.11, Figure 4.17). Overall, according to the ITI scores the communities in both the fish farm and the reference areas were indicative of 'changed' conditions.

Table 4.10 Summary statistics for 1mm sieved replicate (n=2) infaunal grab samples collected in South Uist at reference sites (Stations 12 and 13) and on a transect running north from the fish farm. Statistics show the total number of species (S) and total number of individuals (N) in both grabs together with Simpson's dominance index (D), Pielou's evenness index (J'), Shannon-Wiener's diversity index (H') and Infaunal Trophic Index (ITI) score

	S	**N**	**D**	**J'**	**H'(log$_e$)**	**ITI score**
Station 11 (0m)	59	3311	7.156072	0.561658	2.290182	45.024
Station 10 (25m)	77	1010	10.9863	0.722102	3.136671	59.013
Station 9 (50m)	44	296	7.55664	0.760781	2.878938	51.341
Stn12–ref	88	783	13.05692	0.746491	3.342292	51.154
Stn13–ref	55	463	8.798045	0.684838	2.744375	49.460

Figure 4.16 Mean number of taxa recorded in replicate 0.1m^2 grab samples taken on reference maerl beds and on a transect from 0–50m north of salmon cages in South Uist. Error bars are +Standard Deviation with the number of replicates shown

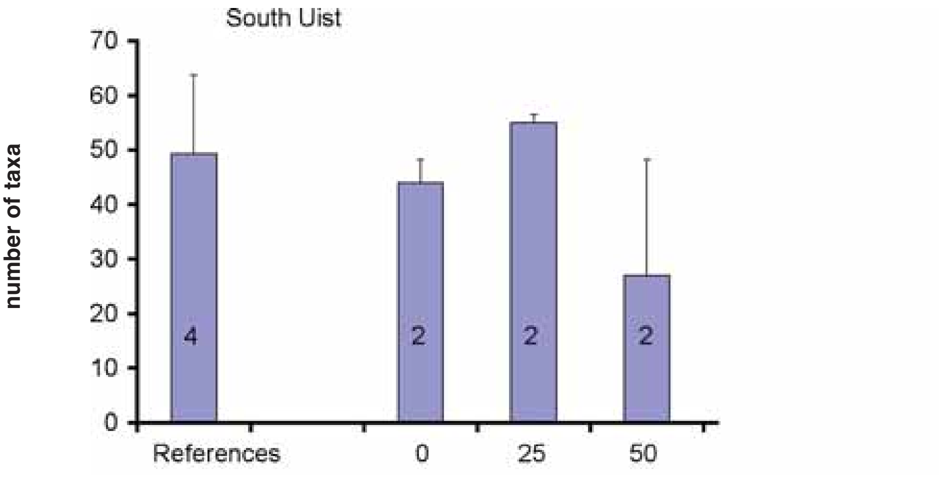


Figure 4.17 Mean number of individuals recorded in replicate 0.1m^2 grab samples taken on reference maerl beds and northwards of salmon cages in South Uist. Error bars are +Standard Deviation with the number of replicates shown

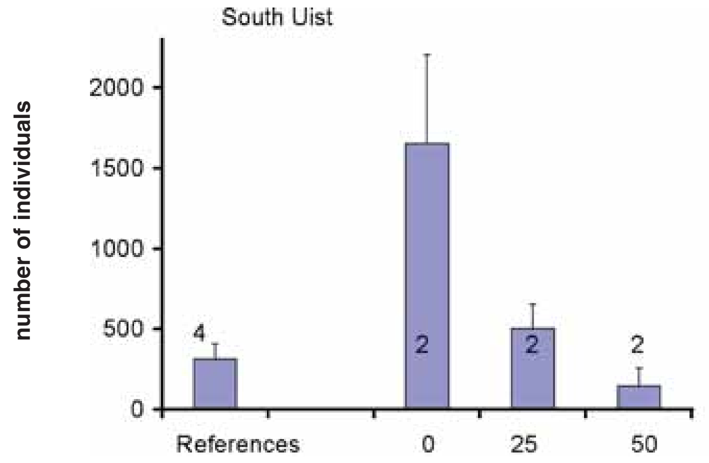
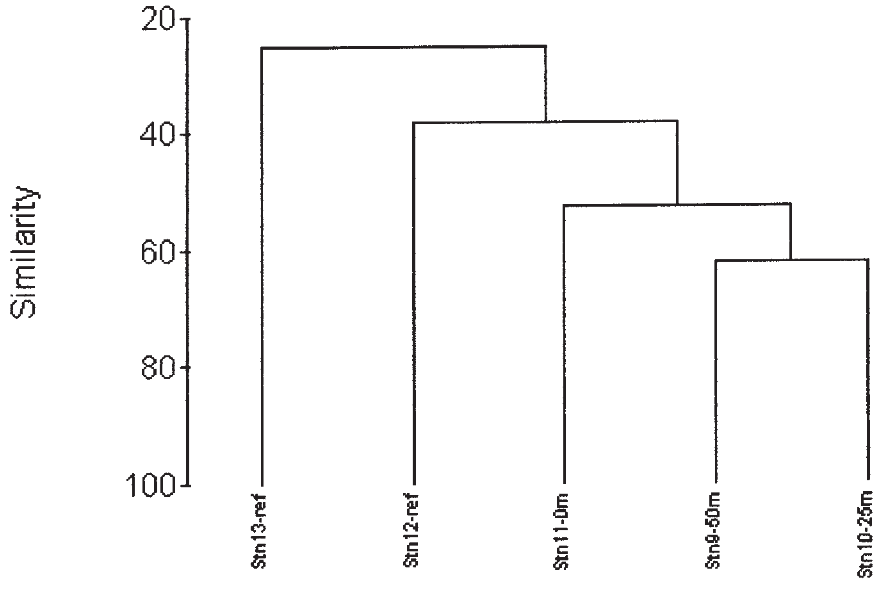


Table 4.11 Mean number (± SE) of opportunists recorded in replicate 0.1m^2 grab samples from reference maerl beds and 0–50m north of salmon cages in South Uist. Note their high abundances near cages

Taxa	0m (n=2)	25m (n=2)	50m (n=2)	Ref sites (n=4)
Capitella capitata	13 ± 7.0	3 ± 2.1	0	<1
Tubificoides benedii	470 ± 13	40 ± 52	38 ± 30	46 ± 79
Socarnes erythrophthalmus	86 ± 1	37 ± 26	2.5 ± 2	<1

Figure 4.18 Dendrogram of Bray-Curtis similarity indices of infauna from South Uist standardised using log X+1 transformation



5 DISCUSSION

SEPA policy and SNH guidance on the location of marine fish farms is to encourage the movement of cages away from enclosed sites with low current speeds to areas with stronger currents to aid dispersion of wastes and lessen the potential impact of these wastes upon the seabed around the cages. This is because a lower load of organic waste per unit area on the seabed allows the infauna to assimilate the material removing it from the environment and allowing the sediments to remain within the limits of quality standards. This aspiration to move to more dispersive locations, along with recent improvements in cage technology, has led to an increase in applications from fish farm operators to relocate to sites in wave-sheltered areas with strong water flows. These are locations that may be above or adjacent to maerl beds. Given the high conservation interest of maerl beds (reviewed by Donnan & Moore, 2003), this project has aimed to improve the basic scientific knowledge that is available for dealing with these applications.

The requirement to implement the EU Water Framework Directive to coastal or 'transitional' waters to ensure good ecological status is likely to be an additional factor in assessing fish farm applications and a new driver in developing management measures in order to ensure good ecological status of coastal waters is delivered.

This study has used a range of survey techniques to investigate the effects of fish farm deposition on maerl beds. As well as providing an insight into the effects of fish farm deposition, the use of these different methods has allowed a comparison of the effectiveness of different survey techniques in monitoring effects of fish farms. In particular the particle tracking modelling has offered an insight into the effectiveness of the model at predicting the effects of fish farm deposition in environments with firm seabeds and strong tidal flows.

The three study sites were situated in areas of strong (>0.4m s^{-1}) tidal streams. At Shetland there were sufficiently detailed current measurements to allow particle tracking modelling using DEPOMOD to predict the fate of organic waste and its effects on seabed communities. The model predicted that even at the highest feeding rates, more than 99% of this material would be exported over time from a 1km^2 area surrounding the farm and that this would have minimal effects on the benthos. Detailed hydrographic information was not available for the Orkney and South Uist fish farms, but the high current speeds measured at these sites suggest that the DEPOMOD model would also predict significant export from a 1km^2 grid around those farms. Thus the model predicted that locations where maerl is present could provide suitable locations for fish farm installations because any impacts would be likely to be minimal. However, *in situ* surveys as part of this project showed that particulate fish farm waste was present on the seabed around the fish farms and that this caused reductions in live maerl cover and affected the infauna with disruptions to the trophic balance of the communities present.

This discrepancy between the predicted and observed effects of fish farm deposition in conditions of strong tidal conditions highlights potential errors in the modelling used to license fish farms in areas of strong tidal flows. With the increased number of applications for fish farms in strong tidal conditions, it is important for licensing purposes to have a technique which is proven to be able to predict the effects of fish farms on benthos in these highly dispersive environments.

A variety of factors could account for the inconsistency between the predicted and recorded effects of fish farms on the benthos. A likely explanation relates to the conditions for which the DEPOMOD model was developed and validated. The DEPOMOD model has been validated using a particulate tracer study on silty mud in sheltered sea loch conditions, which is typical under most Scottish fish farms (Cromey *et al.*, 2002b). However, it has not been validated for maerl substrata and the near bed current speeds at the three sites in this study fall outside the range for which DEPOMOD has been validated.

The matrix-like structure of maerl beds is likely to also contribute to material accumulating at rates in excess of those predicted by DEPOMOD. Divers observed that the intricate matrix of interlocking maerl thalli, stones and shells was able to trap organic wastes from the fish farms. This means that particles which have been deposited on the seabed are less likely to re-suspend compared to particles deposited on a soft sediment seabed. This relates to the consolidation time in the DEPOMOD resuspension module. This was set at 4 days as this was the period used in the validation studies. However, if the particles are trapped within a few hours, then for the purposes of implementing the resuspension module, they could be considered consolidated.

Another factor that influences the distribution of deposited organic particulates is wave action. Studies of an open bay maerl bed in the Firth of Clyde showed that high near-bottom turbulence during occasional storms flushed-out fine particulates and resculpted the maerl bed topography into a series of megaripples (Hall-Spencer & Atkinson, 1999). Such megaripples were also observed in an open bay maerl site in Shetland where food and faeces were building-up around the fish farms. The food and faeces may therefore be redistributed over a wider area during winter storms.

The results suggest that in order to use DEPOMOD for predicting effects of fish farms near maerl sites, DEPOMOD would need to be specifically validated for maerl substrata. Because this study has found that DEPOMOD under-estimated the effects of deposition outside the conditions for which it was validated, consideration should be given to restricting its use to environmental conditions in which it has been validated. The limitations of numerical models at predicting the seabed effects in locations with strong tidal streams have already been acknowledged by SEPA (2004). SEPA have recognised that numerical models, such as AUTODEPMOD(V2), may underestimate impacts at well-flushed sites and that because these models have been designed for soft sediment environments, they are not suitable for uncritical application to maerl beds.

The field surveys have found that at all three sites the fish farms affected the maerl and associated fauna. All of the reference sites (two in Shetland, two in Orkney and two in South Uist) showed no visible signs of organic enrichment and exhibited high levels of live maerl cover and diversity of the associated faunal communities. By contrast, visible signs of organic enrichment (feed pellets, fish faeces and/or *Beggiatoa* mats) were present on the seabed around each of the cages in Shetland, Orkney and South Uist. The area of organic enrichment was largest at the South Uist fish farm, where current speeds were slowest and which was most sheltered from wave action. At Orkney feed pellets were found out to a distance of 100m. However, it should be noted that this distance represents the outer survey points on the transect and therefore it is likely that the footprint of effect extends beyond this distance.

The deposition of organic waste from the fish farms was found to affect a number of different aspects of the benthic community. Most noticeably, the presence of organic waste affected the percentage cover of live versus dead maerl on the seabed. Each of the reference sites had a significantly higher percentage cover of maerl (*P. calcareum*) that was live than the fish farm sites. Maerl was predominantly dead near the cage edges with the proportion of live maerl increasing with distance from the farms. Live maerl close to cage edges had a mottled, unhealthy appearance due to phycobilin pigment loss. This ties in with experimental laboratory evidence which has shown that maerl is particularly sensitive to siltation and sediment chemistry

(Wilson *et al.*, 2004). The laboratory experiments undertaken by Wilson *et al.* (2004) demonstrated that maerl was affected by siltation of fine sediments due to the reduction of water movement around the thalli which probably limits gaseous exchange with detrimental effects on the algae. The deposition of organic particulates around the fish farms therefore probably affected the maerl through this mechanism rather than through reducing the availability of light.

The impact on the health of the maerl thalli is of significance because maerl is very slow growing (it grows circa 1mm per year forming seabed deposits that take 1000s of years to accumulate (Blake & Maggs, 2003)) and therefore has a very limited capacity to recover from damage caused by fish farm deposition. Hence the effects of deposition on maerl are very long-term. This contrasts with the effects of organic waste on muddy seabeds, where the infauna are able to assimilate the material removing it from the environment and the benthos has the capability to recover from the deposition of organic waste within relatively short-time periods.

During the surveys, it was recorded that the deposition of organic waste also affected the epiphytes and epifauna associated with the maerl. The organic waste caused a reduction in the abundance of some species (such as the alga *T. intricata*) but an increase in the abundance of scavenging macrofauna. Between 10 and 100 times as many scavenging macrofauna (eg whelks, crabs and starfish) were recorded close to the cages than at reference sites. It is expected that the macrofauna were attracted to feed on waste food particles or high abundances of infauna some of which (such as *C. capitata)* were superabundant close to the cage edges. However in some locations, for example immediately beneath the cages in South Uist, some of the macrofauna were dead or dying and it is thought that conditions were too anoxic for even these animals to survive.

The infaunal communities of the maerl beds also showed clear effects due to the presence of the fish farms. At the reference sites infaunal analyses of samples confirmed that Scottish maerl beds can be highly diverse. The polychaete and crustacean components stood-out as being particularly rich, as reported in French and Irish maerl deposits (Cabioch, 1968; Keegan, 1974; Grall & Glémarec, 1997a; De Grave & Whitaker, 1999). The most comprehensive data sets in this study came from core samples from Shetland and Orkney. At these sites marked reductions in diversity of the infauna were recorded around fish farms. In Shetland, ostracods, isopods, tanaids and cumaceans were all prominent in reference site samples but significantly depleted both in diversity and abundance out to a distance of 100m from the farm. Shifts in trophic status and community structure are typical effects of organic enrichment in marine sediments (Clark, 2001) and were noted at all three fish farm sites. Core sampling showed that some species were super-abundant in sediment collected near to the cages, such as the organic pollution indicator *C. capitata* (see Grassle & Grassle, 1976), the hypoxia and sulphur resistant *T. benedii* (see Giere *et al.*, 1999) and the scavenger *S. erythrophthalmus*.

Maerl beds typically occur in areas of low siltation and therefore it is to be expected that many of the species which occupy these habitats are habituated to low levels of siltation and would be sensitive to deposition of fine particles. It is therefore not surprising that the infauna of the maerl beds was affected by organic waste deposited around the fish farms. Reductions in the diversity of infaunal communities of maerl beds, similar to those recorded in this study, have been linked to anthropogenic eutrophication and organic enrichment in the Bay of Brest (Grall & Glémarec, 1997a,b) and divers noted 'fungi and bacteria' on maerl under fish cages in Co, Galway, Ireland (Maggs & Guiry, 1987).

Although marked effects of fish farms on maerl beds were recorded at all three study sites, the extent of the impact and magnitude of the effect varied from site to site. In terms of visible effects on the seabed through the presence of organic waste, the greatest area affected was recorded in South Uist. Although the infaunal analysis results for South Uist cannot be accurately compared to Shetland and Orkney, due to a difference in sampling method (grabs rather than cores were used) and sampling locations, the effects of the fish farms on the infauna were most marked at Shetland. The overall effect of the fish farms on the infaunal community appeared less severe at Orkney than at Shetland when measured using the ITI scores. These differences could be due to a variety of factors. A likely explanation is that the cages at Orkney had been recently moved to an area of sandy seabed with scattered maerl and therefore the seabed may have only been recently subjected to increased organic waste and/or the fauna of the sandy seabed were more resilient to input of organic particulates. However, there were differences in all three sites in terms of operating methods and hydrographic conditions and these could also account for the differences observed. In particular different methods for feeding the fish were used at the sites, ranging from an automated feeding system at Shetland to feeding by hand in Orkney. Different lifestages of salmon were also stocked at the different sites, which may affect the feeding regime, for example smolts were present at Orkney. The sites also varied in their hydrographic conditions with the South Uist site being more sheltered from wave action than either Shetland or Orkney. It is noteworthy that despite these different conditions and feeding regimes, the fish farms still had evident effects on the maerl beds and fauna at all three sites.

A review of historical monitoring reports has shown that many of the pollution effects recorded in this study had been noted at the fish farms previously. The Shetland farm had been sited on 90% live maerl in 1991 but within three years maerl had started to die back with accumulations of fish feed, anoxic sediment and *Beggiatoa* mats. The cages were subsequently moved to a fresh area of live maerl and the cycle was repeated. Compared to the results of monitoring undertaken as part of CoPA consents, this study has in general found more extensive effects than those recorded by the consent monitoring. This is likely to be due to a difference in the survey methods. The surveys undertaken for this study were in general more extensive and detailed than those undertaken for monitoring surveys. This has allowed effects of organic waste to be detected where they might otherwise have been missed.

The use of different survey techniques during this study has allowed a comparison of different techniques. It is considered that the use of diving has considerably enhanced the results of this study compared to remote survey techniques such as grab sampling. By having divers on the seabed, the visual appearance of the seabed and features such as presence of *Beggiatoa* and epifaunal could be accurately noted. However, it should be noted that there are greater health and safety implications associated with diving compared to remote survey techniques. It is considered that results were also enhanced by the divers being trained marine biologists as this allowed them to identify epifauna *in situ* and detect subtle effects (such as the presence of mottled maerl fragments) which may have been missed by non-biologists. It is considered that a combination of survey methods is most accurate at detecting and monitoring the effects of fish farms on maerl habitats. It is felt that the most useful parameters to be measured in this environment are (a) the percentage live versus dead maerl by *in situ* estimates; (b) visual observations such as presence of feed pellets and *Beggiatoa* mats and scavenging macrofauna; and (c) infaunal sampling using 1mm mesh. Survey techniques which did not yield useful results were chemical testing, particle size analysis and photoquadrats.

This study has shown that the salmon farms had demonstrable detrimental effects on the conservation status of the maerl beds studied to distances of at least 100m from the cage edges. The 'rotation system' whereby cage positions are rotated to allow muddy sea loch habitats time to process organic waste should not be applied to maerl habitats because of the longevity of the damage caused. High organic loading of sediment results in the long-term loss of living maerl, upon which generation of the habitat depends. The rotation system on muddy habitats relies on the fact that many species are deposit feeders, well adapted for processing organically rich fine particulate material. In contrast, many species at shallow high energy sites (eg maerl, sponges, hydroids, soft corals and bryozoans) are intolerant of smothering by organic particulates. If such sites are to be sacrificed for fish farm production, the most environmentally sensible means to manage these sites would be to ensure that the cages are not then moved around the area.

A point worth noting is that maerl fragments are often transported in and out of areas of the seabed during storm events. Thus "impacted" maerl fragments close to a fish farm may be transported by waves to a non-impacted area of seabed. The effect of this is essentially to increase the area of seabed affected by the fish farm. Conversely however, healthy maerl particles may be transported by waves towards a fish farm which may introduce healthy fragments into an impacted habitat and may serve to maintain the health of seabed beneath the fish farm.

In summary, the results of this study indicate that whilst the movement of fish farms away from sheltered environments to more dispersive locations is in principle a good idea, care needs to be taken in selecting appropriate sites. This is because many of the habitats and species present within these dispersive environments are habituated to conditions of low siltation and sensitive to increased siltation. This renders the communities more sensitive to the presence of organic waste than species associated with sheltered muddy habitats. Furthermore, in most locations with strong tidal streams, the tidal streams follow a diurnal pattern with regular periods of slack water. During slack water organic particulates can settle onto the seabed, thus although overall these conditions are more dispersive than areas of low tidal flow, significant deposition of organic particulates can still occur at slack water, albeit sometimes on a temporary basis. The effect of this deposition is exacerbated in maerl habitats where the interlocking matrix of the maerl allows particulates to accumulate within the matrix essentially preventing them being resuspended as the speed of the tidal stream increases.

Care also needs to taken when transferring monitoring methods from sheltered muddy habitats to more dispersive locations, particularly because most fish farm methods have been developed for sheltered muddy habitats. This is particularly the case with numerical models which have been validated in sheltered sea loch conditions, but the principle also applies to benthic survey techniques which may be appropriate for soft sedimentary habitats but inappropriate in firmer substrata.

6 RECOMMENDATIONS AND FURTHER WORK

A variety of survey methods have been used in this study to investigate the effects of fish farm deposition on maerl beds. This has allowed a comparison of the efficiency of different survey methods. As a result of this the following recommendations are made for methods to be used in surveys on maerl beds aimed at monitoring or predicting the effects of fish farms:

- this study found that fish farm deposition had an effect on the physical characteristics of the seabed, the abundance of epibenthos, the percentage live maerl cover and the infaunal communities. It is therefore recommended that if monitoring studies are carried out at fish farms near maerl beds, they should focus on these parameters;
- with regard to survey techniques, it was found that the visual assessment of the seabed provided a lot of information that would not have necessarily been detected by remote survey techniques such as grabs. It is therefore recommended that surveys should include diving work to allow these visual assessments, amongst other measurements, to be made. In addition diving work should be carried out by experienced marine biology divers who are able to identify marine fauna and flora *in situ*;
- it was found that redox measurements were not useful for measuring the effects of fish farm deposition, most probably due to the open nature of the maerl habitats. It is therefore recommended that this measurement is not used for monitoring effects of fish farms where maerl is present;
- the most effective and accurate method of estimating the percentage cover of live and dead maerl is through *in situ* diver observations. This is because divers are able to survey wide areas by eye and search through seabed material manually. They are also able to locate live maerl when it is heavily epiphytised by foliose and filamentous seaweeds or covered in a layer of fine particulate matter. It is also quicker than subsequent analysis of photographs or video. It is therefore recommended that the percentage live versus dead maerl is estimated *in situ*. If a visual record is required for archiving, it is recommended that quadrats are filmed on video rather than using stills photography, as this provides a greater level of detail. Consideration could also be given to using stills photography of small areas (such as 10cm x 10cm) in order to capture sufficient detail;
- scanning electron microscopy was used to identify the species of maerl and condition of the maerl thalli. This technique could potentially be used for monitoring of the condition of maerl beds. However, it is not recommended that it is incorporated into monitoring programmes because it is an expensive technique which requires specialist equipment and expertise and can only be done in a few locations in the UK. Furthermore an indication of the condition of maerl can be gained by examination of the thalli in the field, for example it is possible to tell if they are dead or alive or mottled, and therefore it is not considered that the extra expense of SEM is justified;
- comparison of sieving of infaunal samples from Shetland using a 0.5mm mesh and a 1mm mesh found that only 21 additional taxa were recorded using the 0.5mm mesh, which represented less than 10% of the total number of taxa recorded. Considering that effects of the fish farms on infauna were detected using the 1mm mesh, it is considered that sieving using a 1mm mesh is sufficient for the purposes of detecting effects on infaunal communities;
- with regard to particle size analysis, it was found that dry sieving did not adequately record the percentage of fine particles. It is therefore recommended that a method which more accurately records the presence of fines is used for future surveys.

In terms of further work, it would be valuable to study the recovery rates of maerl bed communities following the removal of fish farming. Although the maerl thalli are unlikely to recover if they have suffered mortality as a result of fish farming, the infaunal communities have the potential to recover and it would be useful to know the timescale over which this might occur.

In several of the study sites, the effects of fish farm deposition were observed to extend beyond the study area (ie beyond 50m or 100m). For the purposes of licensing, it would be useful to know the extent of the area that can be affected by fish farming and therefore it is recommended that further investigations take place to determine the spatial extent of impacts on maerl beds.

The predictions of the particle deposition modelling did not coincide with the effects of deposition observed during the field surveys. It is therefore recommended that further refinement of DEPOMOD takes place in order that it can be used to accurately predict the effects of deposition in strong tidal flow conditions and with slack waters and complex seabed structures.

This report gives a broad indication of the sensitivity of maerl to fish farming operations. The report provides technical assistance and advice to SNH, SEPA and other relevant authorities with respect to the Water Framework Directive. It is hoped that this report will assist in the development of a suite of policies and management measures that will ensure a sustainable aquaculture industry that is compatible with the target of delivering good ecological status in Scotland’s coastal waters.

7 REFERENCES

Adey, W.H. & Adey, P.J. (1973). Studies on the biosystematics and ecology of the epilithic crustose Corallinaceae of the British Isles. *British Phycological Journal*, **8**, 343–407.

Adey, W.H. & McKibbin, D.L. (1970). Studies on the maerl species *Phymatolithon calcareum* (Pallas) nov. comb. and Lithothamnion corallioides Crouan in the Ria de Vigo. *Botanica Marina*, **13**, 100–106.

BIOMAERL Team, (1999). *Final Report, BIOMAERL project (Coordinator: P.G. Moore, University Marine Biological Station Millport, Scotland),* EC Contract No. MAS3–CT95–0020, (in 2 vols), 1: 1–541, 2: 542–973pp + Appendix.

Birkett, D.A., Maggs, C.A. & Dring, M.J. (1998). *An overview of dynamic and sensitivity characteristics for conservation management of marine SACs*, Vol. 5, *Maerl*, [UK Marine SACs Project], Scottish Association for Marine Science, Scotland, 116 pp.

Blake, C. & Maggs, C.A. (2003). Comparative growth rates and internal banding periodicity of maerl species (Corallinales, Rhodophyta) from northern Europe. *Phycologia*, **42**, 606–612.

Blunden, G. *et al*. (1981). The composition of maerl beds of economic interest in northern Brittany, Cornwall and Ireland, in *Proceedings of the Xth International Seaweed Symposium*, Walter de Gruyter & Co., Berlin, 651–656.

Blunden, G. *et al*. (1977). The composition of maerl from the Glenan Islands of Southern Brittany. *Botanica Marina*, **20**, 121–125.

Bosence, D.W.J. (1979). Live and dead faunas from coralline algal gravels, Co. Galway, *Palaeontology*, **19**, 365–395.

Bosence, D.W.J. & Wilson, J. (2003). Maerl growth, carbonate production rates and accumulation rates in the Northeast Atlantic. *Aquatic Conservation, Marine and Freshwater Issues*, **13**, 21–32.

Brazier, P. (2001). Procedural Guideline No. 3–8. Quantitative sampling of subtidal sediment biotopes and species using diver-operated cores. *In*: Davies, J. *et al*, eds. *Marine Monitoring Handbook*. Joint Nature Conservation Committee, Peterborough.

Brown, J.R., Gowen, R.J. & McLuscky, D.S. (1987). The effect of salmon farming on the benthos of a Scottish sea loch. *Journal of Experimental Marine Biology*, **109**, 39–51.

Cabioch, L. (1968). Contribution à la connaissance des peuplements benthiques de la Manche occidentale, *Cahiers de Biologie Marine*, **9** (5 suppl.), 493–720.

Cabioch, J. (1969). Les fonds de maerl de la baie de Morlaix et leur peuplement végétal. *Cahiers de Biologie Marine*, **10**, 139–161.

Cabioch, J. (1970). Le maerl des cotes de Bretagne et le probleme de sa survie. *Penn ar Bed*, **7**, 421–429.

Cabioch, J. (1974). Un fond du maerl de l'Archipel de Madere et son peuplement vegetal. *Bulletin Societe Phycologique de France*, **19**, 74–82.

Clark, R.B. (2001). *Marine Pollution*. Oxford: Oxford University Press. 237 pp.

Clark, R.N. (2000). The chiton fauna of the Gulf of California rhodolith beds (with descriptions of four new species). *Nemouria – Occasional Papers of the Delaware Museum of Natural History*, **43**, 1–20.

Clarke K.R. & Warwick, R.M. (2001). *Change in Marine Communities: An Approach to Statistical Analysis and Interpretation*. 2nd edition: PRIMER-E, Plymouth, UK, 172pp.

Codling I.D. & Ashley S.J. (1992). Development of a biotic index for the assessment of pollution status of marine benthic communities. *R&D Note 158*, WRc plc.

Cromey, C.J. *et al*. (1998). Modelling the deposition and biological effects of organic carbon from marine sewage discharges. *Estuarine Coastal and Shelf Science*, **47**, 295–308.

Cromey, C.J., Nickell, T.D. & Black, K.D. (2002a). DEPOMOD – modelling the deposition and biological effects of waste solids from marine cage farms. *Aquaculture*, **214**, 211–239.

Cromey, C.J. *et al*. (2002b). Validation of a fish farm waste resuspension model by use of a particulate tracer discharged from a point source in a coastal environment. *Estuaries*, **25**, 916–929.

Davies, I. M. (2000). Waste production by farmed Atlantic salmon (*Salmo salar*) in Scotland. *ICES CM O*, **1**, 1–6.

De Grave, S. & Whitaker, A. (1999). Benthic community re-adjustment following dredging of a muddy-maerl matrix. *Marine Pollution Bulletin*, **38** (2), 102–108.

Donnan, D.W. & Moore, P.G. (2003). International workshop on the conservation and management of maerl. *Aquatic Conservation, Marine and Freshwater Issues*, **13**, 1–78.

Emerson, C. (1999). Aquaculture impacts on the marine environment. Hot topic series provided by Cambridge Scientific Abstracts. http://www.csa.com/hottopics/aquacult/oview.html

FAO (2002). *The state of world aquacultures.* ISBN 92–5–104842–8.

Freiwald, A. & Henrich, R. (1994). Reefal coralline algal build-ups within the Arctic Cycle: morphology and sedimentary dynamics under extreme environment seasonality. *Sedimentology*, **41**, 963–984.

Giere, O., Preusse, J.-H., & Dubilier, N. (1999). *Tubificoides benedii* (Tubificidae, Oligochaeta) – a pioneer in hypoxic and sulfidic environments. An overview of adaptive pathways. *Hydrobiologia*, **406**, 235–241.

Grall, J. & Glémarec, M. (1997a). Using biotic indices to estimate macrobenthic community perturbations in the Bay of Brest, *Estuarine, Coastal and Shelf Science*, **44** (suppl A), 43–53.

Grall, J. & Glémarec, M. (1997b). Biodiversité des fonds de maerl en Bretagne: approche fonctionnelle et impacts anthropogeniques. *Vie et Milieu*, **47**(4), 339–349.

Grall, J. & Hall-Spencer, J.M. (2003). Problems facing maerl conservation in Brittany. *Aquatic Conservation, Marine and Freshwater Ecosystems*, **13**, 55–64.

Grant, A. & Briggs, A.D. (1998). Use of Invermectin in marine fish farms: some concerns. *Marine Pollution Bulletin*, **36**, 566–568.

Grassle, J.F. & Grassle, J.P., (1976). Sibling species in the marine pollution indicator (*Capitella*) (Polychaeta). *Science*, **192**, 567–569.

Hall-Spencer, J.M. (1998). Conservation issues concerning the molluscan fauna of maerl beds. *Journal of Conchology*, Special Publication **2**, 271–286.

Hall-Spencer, J.M. (2001a). Maerl – a jewel in the crown of Scotland's Marine Heritage. *Leading Edge, University of Glasgow*, **8**, 2–3.

Hall-Spencer, J.M. (2001b). Maerl – a spectacular Firth of Clyde habitat. *In: The ecology and management of the Firth of Clyde*. Firth of Clyde Forum.

Hall-Spencer, J.M. & Atkinson, R.J.A. (1999). *Upogebia deltaura* (Crustacea, Thallassinidea) in Clyde Sea maerl beds, Scotland. *Journal of the Marine Biological Association of the UK*. **79**, 871–880.

Hall-Spencer, J.M., Grall, J. & Moore, P.G. (2003). Bivalve fishing and maerl-bed conservation in France and the UK—retrospect and prospect. *Aquatic Conservation, Marine and Freshwater Ecosystems*, **13**, 33–41.

Hardiman, P.A., Rolfe, M.S. & White, I.C., (1976). *Lithothamnion* studies off the south west coast of England. *Report to the Fisheries Improvement Committee. International Council for the Exploration of the Sea (CM Papers and Reports)*, CM 1976/K:**9**, 13 pp.

Hauton, C., Hall-Spencer, J.M. & Moore, P.G. (2003). Ecological impacts of hydraulic bivalve dredging on maerl. *ICES Journal of Marine Science*, **60**, 381–392.

Howson, C.M. & Picton, B.E.(eds) (1997). *The species directory of the marine fauna and flora of the British Isles and surrounding seas*. Belfast and Ross-on-Wye: Ulster Museum and The Marine Conservation Society.

Irvine, L.M. & Chamberlain, Y.M.C. (1994). *Seaweeds of the British Isles,* Volume 1, Part 2B. London: British Museum (Natural History). 276 pp.

Kamenos, N.A., Moore, P.G., & Hall-Spencer, J.M. (2003). Substratum heterogeneity of dredged versus un-dredged maerl grounds. *Journal of the Marine Biological Association of the UK*, **83**, 411–413.

Kamenos N.A., Moore P.G., & Hall-Spencer, J.M. (2004a). Small-scale distribution of juvenile gadoids in shallow inshore waters; what role does maerl play? *ICES Journal of Marine Science*, **61**, 422–429.

Kamenos, N.A., Moore, P.G., & Hall-Spencer, J.M. (2004b). Attachment of the juvenile queen scallop (*Aequipecten opercularis* (L.)) to maerl in mesocosm conditions; juvenile habitat selection. *Journal of Experimental Marine Biology and Ecology*, **306**, 139–155.

Kamenos, N.A., Moore, P.G., & Hall-Spencer, J.M. (2004c). The importance of maerl grounds for recruitment of queen scallops (*Aequipecten opercularis*) and other invertebrates. *Marine Ecology Progress Series*, **274**, 183–189.

Keegan, B.F. (1974). The macrofauna of maerl substrates on the west coast of Ireland, *Cahiers de Biologie Marine*, 15, 513–530.

King, R.J. & Schramm, W. (1982). Calcification in the maerl coralline alga *Phymatolithon calcareum*: effects of salinity and temperature. *Marine Biology*, **70**, 197–204.

Kjellmann, F.R. (1883). Norra Ishavets Algflora. *Vega-expeditionens Vetenskapliga lakagelser*, **3**, 1–431.

Maggs, C.A. (1983). A *phonological study of the epiflora of two maerl beds in Galway Bay*. Unpublished PhD Thesis, Queen's University Belfast, 346 pp.

Maggs, C.A. & Guiry, M.D. (1982). Morphology, phenology and photoperiodism in *Halymenia latifolia* Kutz. (Rhodophyta) from Ireland. *Botanica Marina*, **25**, 589–599.

Maggs, C.A. & Guiry, M.D. (1987). *Gelidiella calcicola* sp. nov. (Rhodophyta) from the British Isles and Northern France. *British Phycological Journal*, **24**, 253–269.

Maggs, C.A. & Guiry, M.D. (1989). A re-evaluation of the crustose red algal genus *Cruoria* and the family Cruoriaceae. *British Phycological Journal*, **24**, 253–269.

McGinnity, P. *et al.* (1997). Genetic impact of escaped farmed Atlantic salmon (*Salmo salar*) on native populations: use of DNA profiling to assess freshwater performance of wild, farmed and hybrid progeny in a natural river environment. *ICES Journal of Marine Science,* **54**, 998–1008.

McMaster, R.W. & Conover, J.P. (1966). Recent algal stromatolites from the Canary Islands. *Journal of Geology*, **80**, 611–616.

Mora Bermúdez, J. (1980). *Poblaciones benthonicas de la Ria de Arosa*. PhD thesis, The University of Santiago de Compostela, Spain.

Myers, A.A. & McGrath, D. (1980). A new species of *Stenothoe* Dana (Amphipoda, Gammeridea) from maerl deposits in Kilkeran Bay. *Journal of Life Sciences, Royal Dublin Society*, **2**, 15–18.

Myers, A.A. & McGrath, D. (1983). The genus *Listriella* (Crustacea: Amphipoda) in British and Irish waters, with the description of a new species. *Journal of the Marine Biological Association of the United Kingdom*, **63**, 347–353.

O'Connor, B.D.S. & Shin, P.K.S. (1983). *Hesiospina similis* (Hessle) (Polychaeta, Hesionidae) from Galway Bay, west coast of Ireland, with notes on its taxonomic status and distribution. *Cahiers de Biologie Marine*, **24**, 355–361.

OSPAR, (2004). Meeting of the Biodiversity Committee in Bruge, 16–20 February 2004. Summary Record BDC 04/14/1.

Pauly, D. (2002). Towards sustainability in world fisheries. *Nature*, **418**, 689–695.

SEPA, (2003). *Regulation and monitoring of marine cage fish farming in Scotland – a procedures manual.* Dowloaded from www.sepa.gov.uk

SEPA, (2004). *Improving the regulation of environmental impacts from marine caged fish farms: Revised methodology to assess impacts in marine sediments and derive consent limits on maximum fish biomass.* 21st December 2004. Consultation paper.

Southward, E.C. (1957). The distribution of Polychaeta in offshore deposits in the Irish Sea. *Journal of the Marine Biological Association of the United Kingdom.* **36**, 49–75.

Steller, D.L. *et al.* (2003). Rhodolith bed diversity in the Gulf of California: the importance of rhodolith structure and consequences of disturbance. *Aquatic Conservation, Marine and Freshwater Ecosystems.* **13**, 5–20.

WRc, (1997). *Calculation of additional marine benthic taxa into ITI (UK) feeding groups*. SNIFFER report by WRc plc.

Wilson, S. *et al*. (2004). Environmental tolerances of free-living coralline algae (maerl): implications for European maerl conservation. *Biological Conservation*, **120**, 283–293.

WWF Scotland, (2000). *Scotland's secret – aquaculture, nutrient pollution eutrophication and toxic blooms.* Aberfeldy: WWF Scotland. http://www.wwf-uk.org/filelibrary/pdf/secret.pdf

8 GLOSSARY

ALLOWABLE ZONE OF EFFECTS (AZE)	The area (or volume) of seabed or receiving water body in which SEPA will allow some exceedance of the relevant environmental quality standard or some damage to the environment
ANOXIC	Devoid of oxygen
BAP	Biodiversity Action Plan
BENTHIC	Pertaining to the bottom (bed) of a water body
BENTHOS	Those organisms attached to or living on, in or near, the seabed, including that part which is exposed by the tides
BIOTURBATION	The mixing of a sediment by the burrowing, feeding or other activity of living organisms
CoPA	Control of Pollution Act 1974
DEPOMOD	Particle Tracking Model
EPIFAUNA	Animals living on the surface of sediments and hard substrates
EPIPHYTES	Plant living on the surface of another plant or animal but not living parasitically
EQS	Environmental Quality Standard
EUTROPHICATION	The over-enrichment of an aquatic environment with inorganic nutrients, especially nitrates and phosphates, often anthropogenic, which may result in stimulation of growth of algae and bacteria, and can reduce the oxygen content of the water
GPS	Global Positioning System
INFAUNA	Benthic animals that live within the seabed
ITI	Infaunal Trophic Index
MACROFAUNA	Animals exceeding 1mm in length
MEGARIPPLE	Ripples of large wavelength formed in coarse sediment by moderate/strong currents
MNCR	Marine Nature Conservation Review

NMBAQC	National Marine Biological Analytical Quality Control
ORGANIC ENRICHMENT	The addition of particulate or dissolved organic matter to a water body beyond the assimilative capacity of the receiving waters is insufficient to degrade the organic matter
ORP	Oxidation-Reduction Potential
OSPAR	OSPAR Convention for the Protection of the Marine Environment in the North East Atlantic
PSA	Particle Size Analysis
SAC	Special Areas of Conservation
SEM	Scanning Electron Microscopy
SEPA	Scottish Environment Protection Agency
SNH	Scottish Natural Heritage
THALLUS	A relatively undifferentiated plant body lacking true leaves, stems and roots
UKAS	United Kingdom Accreditation Service
WWF	World Wide Fund for Nature