ECASA Study Site Report

Loch Creran

Scotland

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Scottish Association for Marine Science

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Abbreviations and acronyms

AMA	Area Management Agreement
CHN	Carbon Hydrogen Nitrogen
ECASA	Ecosystem Approach for Sustainable Aquaculture
ECE	Equilibrium Concentration Enhancement
EFCR	Economic Feed Conversion Ratio
LOI	Loss on Ignition
NNR	National Nature reserve
ROV	Remote Operated Vehicle
RSPCA	Royal Society for the Prevention of Cruelty to Animals
SAC	Special Area of Conservation
SAMS	Scottish Association for Marine Science
SEERAD	Scottish Executive Environmental and Rural Affairs Department
SEPA	Scottish Environmental Protection Agency
SMRU	Sea Mammal Research Unit
SQS	Scottish Quality Salmon
SSSI	Site of Special Scientific Interest
TOP	Total Organic Phosphate
TWG	Tripartite Working Group
UoV	University of Venice

1. Introduction to the aquaculture operation

1.1. Introductory background statement

The Company.
Scottish Sea Farms have been established since 1974, and is currently owned by Norskott, a Norwegian company. Scottish Sea Farms produces Atlantic salmon (*Salmo salar*) and employs 300 people in locations across the west coast of Scotland and Shetland. The company has 37 marine sites, 4 freshwater sites and 3 hatcheries, with an output of approximately 22,000 tonnes per annum. Loch Creran has been the site for salmon cages since 1983.

Field Campaign
ECASA contributors: SAMS, IFM-GEOMAR. The ECASA field campaign was carried out during the summer of 2006. The site in Loch Creran was visited on 8, 10 and 17 August 2006 after consultation with the Production Manager, Mr. John Rea.

The following field deployments were made:

- macrobenthos collection
- redox
- chlorophyll bioassay deployment
- megacoring for biogeochemistry

The following laboratory based analyses were carried out:

- particle size analysis
- organic carbon
- Loss On Ignition
- sulphates
- pore water nutrients ammonium, nitrate
- dissolved iron
- dissolved manganese
- total organic phosphate
- chlorophyll bioassay

The procedures used in both field and laboratory work can be found in the protocols document on www.ecasatoolbox.org.uk

This report is intended to present a snapshot of the environmental conditions prevalent at the time of monitoring. Macrofaunal sampling was slightly delayed by failure of the van Veen grab; the sampling was abandoned the following day due to strong gales, and was completed two days after the original sampling.

1.2. Summary statement of key site specific environmental issues

Loch Creran is a semi-enclosed sea loch at the north end of the Firth of Lorn with a constricted opening into the Lynn of Lorn. Loch Creran has recently been assigned a Special Area of Conservation (SAC). The main reason for this designation is the presence of reefs formed by the serpulid polychaete *Serpula vermicularis.* Loch Creran is the only location in Europe where this biogenic reef is found in abundance.

1.3. Information of farmer's environmental strategy:

Scottish Sea Farms environmental policy has been developed to comply with ISO14001 standards. The environmental policy was certified by ISO14001 in 2000 and again in 2003.

Scottish Sea Farms environmental policy is detailed in Appendix 1.

Specific key areas that this policy addresses are:

- Salmon feed suppliers use only sustainable fishmeal sources
- Overall target of zero fish escapes through effective stock management
- Lice monitoring and control to be at least as strict as National Lice Treatment Strategy Guidelines (SQS) with zero gravid lice as a goal
- All sites will actively participate in Area Management Agreements
- The economic Feed Conversion Ratio should meet targeted levels on a crop by crop basis.

Current regulatory status

Scottish Sea Farms have been granted a lease from the Crown Estate to deploy moorings on the sea floor in Loch Creran. SEPA have also granted two discharge consents relating to waste/feed input (there is no feed input restriction), and biomass. In addition to the statutory regulatory regime Scottish Sea Farms have entered into a voluntary management system involving all users within the Loch, developed from the recommendations of the TWG, culminating in an Area Management Agreement.

In Scotland the regulatory controls are maintained by the Scottish Environment Protection Agency (SEPA). These involve regular monitoring of the hydrology around cage sites, water column and sea bed quality. In addition to this there are voluntary Area Management Agreements, which are drawn up primarily to address lice control and its potential impact on wild fisheries.

2. Site specific regulatory and management background

2.1. The regulatory status of proposed location with respect to fish farming developments.

Loch Creran was designated by Scottish Ministers as a Special Area of Conservation (SAC) on 17th March 2005. This site is also referred to as a 'European site' (Regulation 10(1)). Other designations within or adjacent to the Loch Creran marine SAC are: Lynn of Lorn National Scenic Area; Glasdrum National Nature Reserve (NNR); Glasdrum SAC (underpinned by Glasdrum SSSI); Glen Creran Woods SAC; South Shian and Balure SSSI. The Loch Creran marine SAC has been designated for the habitat 'Reefs', which is listed on Annex I of the Habitats Directive. It is also designated for species, due to the presence of the European otter *Lutra lutra* and the common seal *Phoca vitulina* which are both listed as Annex II species under the Habitats Directive.

Under the terms of its classification as an SAC (Council Directive 92/43/EEC), the Loch Creran Marine SAC Management Plan has been formulated to regulate the sustainable development of the loch amongst all stakeholders. These activities are broken down into sections, which are as follows: management of fishing activities (benthic dredging, benthic trawling, creel fishing, whelk fishing, and shellfish diving); shellfish and bait collection from the foreshore; aquaculture activities (finfish farming and shellfish farming); management of recreation and tourism activities (mooring placement, anchoring, scuba diving, charter boat operations); management of effluent discharges and marine dumping (trade effluent, sewage effluent, marine littering and dumping); management of shipping/boating related activities (commercial marine traffic, boat hull maintenance and antifoulant use); management of coastal/marine development and land-use (coastal/marine development, agriculture, forestry, management of scientific research).

2.2. Site description

Loch Creran is a sea loch 12.8 km in length, containing 4 silled basins. The Scottish Sea Lochs catalogue (Edwards and Sharples, 1985) gives some vital statistics which are worth summarising here.

Freshwater is added at a rate of 286.3 x 10^6 m^3 yr^{-1}. This is mixed into the saline loch water by energy supplied from wind and tides. Ignoring the wind component, the mixing energy is a function of the tidal streams crossing the sills and a mixing depth can be calculated. When ranked against other sea lochs, Loch Creran has the second greatest mixing depth and the third greatest ratio of mixing depth to maximum depth. This means that, even without considering wind effects, Loch Creran is typically a well mixed system with no isolation of high density bottom waters. In addition the flushing time (calculated as the ratio of the loch volume to the tidal flow rate) for Loch Creran is around 3 days which means that around 60% of the loch volume is exchanged with coastal waters in that time thereby diminishing the risk of serious accumulation or retention of any soluble contaminants.

The entrance sill which spans from the Isle of Eriska to Dearg Sgeir is 7 m deep and relatively narrow: 320 m wide at low water. This encloses a small outer basin (basin 1), maximally 27 m deep, characterised by strong tidal streams and bounded by the second sill, 11 m depth, between Ceann Garbh and Eilean a' Chruidh. The second basin so formed (basin 2) is the deepest of the 4, at 49 m and is characterised by hard sediments from the second sill to the deepest part and thereafter by soft sediments. The sill is long with strong currents which diminish as the water deepens. The third sill, between Rubha Riabhach and Druim na Claoidh, is 15 m deep. The third basin (basin 3) is characterised by soft sediments for the most part and is relatively shallow having a maximum depth of 27 m but a large area where the depth is between 12 and 20 m with relatively flat bottom topography. The second and third basins, which form the main body of the loch, are often collectively referred to as the main basin. The upper basin (basin 4), delimited by a narrow (100 m at LW), shallow (3 m) sill at the Creagan Narrows has a maximum depth of 37 m. The narrows are characterised by high flow rates and a wide range of hard substrate fauna which attract considerable sport diving interest. The River Creran is the largest single source of freshwater input to the Loch Creran system although there are numerous other small streams and burns.

In summary, the loch is divided into 4 basins. The first of these is dominated by coarse sediments due to the high tidal flows which predominate, as is the seaward end of the second basin. The landward part of the second basin is characterised by soft, enriched, muddy sediments dominated by scavengers (an undescribed biotope) leading on to a less enriched mud characterised by sea pens. Although the main part of the third basin is presently assigned to a similar biotope, there were many fewer sea pens and more evidence of large burrowing animals. The deep part of the upper basin is broadly similar to the major biotope found in the third basin. The sill between the two most inward basins is characterised by hard and gravel sand sediments.

Serpulid reefs occur at high density around the southern fringe of the loch from near to the Sea Life Centre to South Shian Bay. The part of the reef on the northern shore appears to be much less healthy than the southern part with many dead animals and considerable overgrowth of encrusting organisms. The *Modiolus* bed in the upper basin appears to represent an undisturbed biotope.

Several features of Loch Creran are of conservation importance: the tidal rapids near the mouth, at the second sill and at the Creagan narrows; the deep water mud biotopes (at least one of which is currently undescribed) in the second, third and upper basins; the *Modiolus* bed in the upper basin and the limited beds of *Zostera marina*, but the major significance of Loch Creran in conservation terms must be the *Serpula vermicularis* reefs which may be unique in the UK.

2.3. Detailed description of the farm

The site at Loch Creran is a marine salmon farm. Salmon have been produced in Loch Creran since 1983, using alternate site locations. The current development consists of 14*70 m circular cages, 2*80 m circular cages, 3*Storvik Quattro feeding systems and 1 feed barge. Staff facilities are provided on the barge. A toilet empties into a septic tank which is regularly removed and its contents disposed of appropriately.

The site provides employment for 6 full time staff. The cages have been locally built by Fusion Marine, the nets are sourced from within Scotland by Knox Nets. Feed is supplied by Biomar.

The site will provide over a 2 year crop £250,000 in direct staff salaries alone, this production further supports additional employment in processing and associated services.

2.4. Proposed management strategy: biomass, medicines, chemicals, cycle, feed inputs, growth measurements.

The production cycle at Creran is 22 months. The maximum biomass for this cycle is 1500 tonnes with a total production of 2300 tonnes. It is estimated that 2,875 tonnes of feed will be used over the cycle at an FCR of 1.25.At peak production the stocking density is anticipated to be 17 kg m^{-3}. Medicines used at the site are Slice (emamectin benzoate) and Excis (cypermethrin).

2.5. Physical farm logistics, including type of gear used, moorings, access, lighting and anti-predator measures.

The net depth is 14 m below the surface of the Loch. The moorings are a 2*8 strand 45 m grid. Access to the cages is by boat. Lighting on site is minimal; there is a light on the barge, and depending on the stage in the production cycle there will be some lighting below the surface. Airmar acoustic deterrent devices are used to repel seals from the cages, and dead baskets are placed below the nets to remove morts, whose presence would encourage seal predation. The dead baskets are emptied daily. Net tensioning is employed to prevent seal and avian predation on the caged fish and anti-avian predator nets are installed.

2.6. Production and Processing

Live fish are transported by well boat to the processing plant at South Shian for harvesting. The fish are killed by percussion stunning and their gills are cut. All processing is done on site and Scottish Sea Farms have the fastest kill to pack time in the industry. Scottish Sea Farms are RSPCA approved in all matters of fish welfare.

The biological effluent resulting from the processing plant is directed to an effluent plant on site. The water content is treated and discharged back into the loch, the solid residue is sold to an external company and reprocessed.

3. Description of the site and quantification of effects on the environment – existing information only, not collected by ECASA.

3.1. Land use, landscape and visual quality (use maps and photographs)

The surrounding land use is rural, with small scale crofting, mostly sheep rearing, and forestry being the dominant land use. Tourism is an important industry in the area. The loch itself is highly utilized by many different users. There are several mussel farms in the loch, the closest being 800 m away. There is also an oyster farm. Rhu Garbh and the Marine Resource Centre at Barcaldine are busy marinas located in the loch.

Figure 1. Oyster trestles, Loch Creran

Figure 2. Salmon farm, Loch Creran

The Lynn of Lorn National Scenic Area covers the site. This designation means the site is in an area of high visual amenity. Scottish Sea Farms have attempted to minimize the visual intrusiveness of the site by using low profile circular cages. These cages lie very low in the water and are made from low reflective material. The feed barge is the most visible element in the site. It is currently being converted to resemble a traditional fishing boat and so blend in with the surroundings. The presence of the barge removes the need for on site feed storage which would have a higher visual impact.

Figure 3. Mussel farm, Loch Creran

The villages of South Shian and Barcaldine are the only real settlements along the loch, although they do not register on the 1991 census for populations greater than 500. It should be safe to assume that the total population around Loch Creran amounts to less than 500.

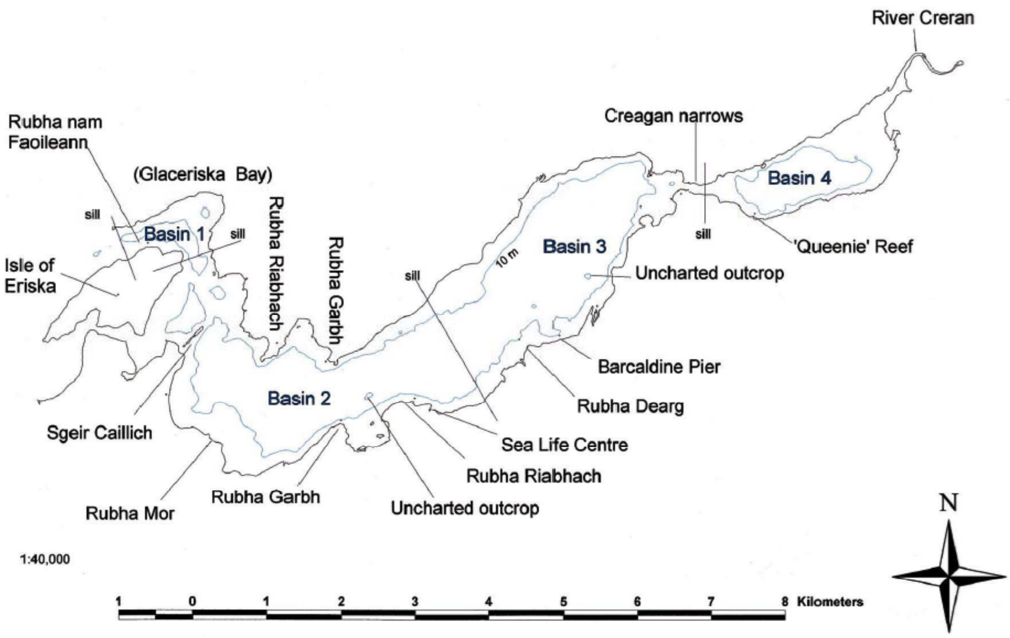

Figure 4. Plan of Loch Creran showing basins and physical features. From Black *et al*., 2000.

3.2. Hydrography and water quality

Loch Creran has 4 main basins separated by narrow sills (Figure 4). The salmon farming sites lie in the outer basin which is 9 km long and has a maximum depth of 49 m. The Loch is relatively sheltered from wave action and has a freshwater run off of 286.30 x 10^6 year $^{-1}$. Loch Creran is a well mixed loch with no isolation of bottom waters. The flushing time is about three days with little risk of accumulation of soluble inputs. The sea bed type in the vicinity of the cages is soft mud.

Current measurements were made at the site by SAMS from 05.04.01 – 23.04.01. Chart datum depth at the site was 27 m and meters were deployed at 2 m, 14 m, and 25 m from the sea bed. Mean current speeds were 5.1 cm s^{-1} near the sea bed, 4.5 cm s^{-1} in the middle of the water column and 8.2 cm s^{-1} near the surface. All three meters show residual water movement to the west, toward the mouth of the loch, with the residual being most pronounced on the subsurface layer. The tidal cycle is clearly defined on the near seabed meter, but less clear on the upper meters.

The important topographical features of Loch Creran are the 2 sills between the farm location in basin 2 and the adjacent sea of the Firth of Lorne. These 2 sills have depths of 7 and 11 m with deeper water either side of the sills, as previously described in section 2.2. Despite these topographic features, the site location in basin 2 is reasonably well flushed with a flushing time of 3 days (zone B) and with moderate current. Although basin 2 is 49 m at its deepest, as there is gently shelving bathymetry in the area deep water isolation is rare. The loch is typically thermally and/or salinity stratified depending on season and rainfall.

Loch Creran has been modelled hydrodynamically using Delft 3D as part of the EU FP6 KEYZONES project (www.keyzones.com), albeit using a coarse grid. Hydrodynamic information for this site has been obtained by site survey only in this present study.

3.3. Bathymetry, geology and habitats.

Soil & geology: Biogenic reef, igneous, mud, sand, sedimentary, shingle .

Geomorphology & landscape: basins, enclosed coast (including embayment), intertidal rock, ob (fjord), subtidal rock (including rocky reefs), subtidal sediments (including sandbank/mudbank), tidal rapids.

The seabed at the study site has been extensively mapped by SAMS as part of a largescale acoustic ground discrimination survey for Scottish Natural Heritage (Black, *et al.*, 2000) (Figure 5). The study site is near to the quantitative station DML2, as well as the ROV dive site 23. The seabed in this area was classified as "fine smooth mud" and the biotope as "sea pens and burrowing megafauna (CMU.SpMeg)" (Connor *et al.*, 1997). There are habitat/biotope/substrate maps available as well as accurate bathymetric data.

3.4. Benthos and sediments

Loch Creran SAC is a site of international conservation importance for reefs (Black, et *al*., 2000). The site is particularly notable for biogenic reefs of the calcareous tubeworm *Serpula vermicularis*, which occur in shallow water around the periphery of the loch. The species has a world-wide distribution but the development of reefs is extremely rare: Loch Creran is the only known site in the UK to contain living *S. vermicularis* reefs and there are no known occurrences of similarly abundant reefs in Europe.

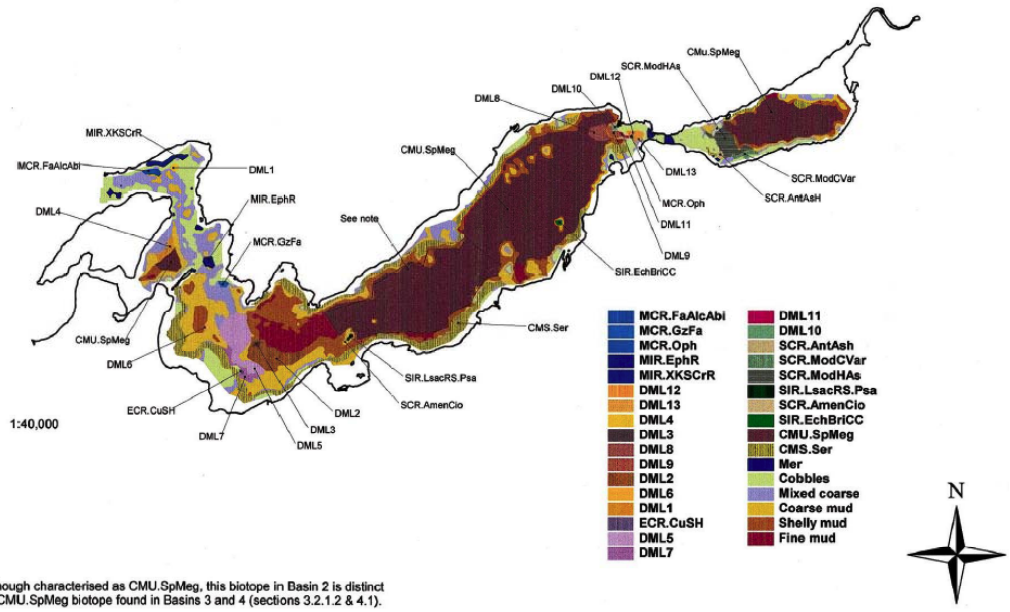

Figure 5. MNCR biotopes in Loch Creran. From Black *et al*., 2000.

Biogenic reefs of the horse mussel *Modiolus modiolus* occur in the upper basin of the loch. *M. modiolus* reefs are an important element of Scotland's marine biodiversity, and are considered to be habitats of high conservation value. The biogenic reefs increase habitat complexity and are colonised by an abundant and diverse faunal assemblage including red alga *Phycodrys rubens*, solitary sea squirts *Pyura microcosmus* and *Ascidiella aspersa*, the sponge *Esperiopsis fucorum*, bivalves *Chlamys varia* and Aequipecten opercularis, and the hydroid *Halecium halecinum*. Predators and scavengers such as the common starfish *Asterias rubens*, swimming crabs Liocarcinus depurator and whelks *Buccinum undatum* are usually associated with the reef. Also present amongst the reef community are porcelain crabs *Pisidia longicornis*, hermit crabs *Pagurus* spp., brittle stars *Ophiothrix fragilis* and feather stars *Antedon bifida*. Localised areas of bedrock reef occur within the loch and support further species rich assemblages that are characteristic of a range of tidal stream conditions. An area of very sheltered infra-littoral bedrock in the upper basin is characterised by a dense canopy of the kelp *Laminaria saccharina*. The sea urchin *Psammechinus miliaris*, the squat lobster *Munida rugosa*, the hermit crab *Pagurus bernhardus* and the queen scallop *Aequipecten opercularis* usually occur on or around the reef. Filter-feeders, thrive in the strong currents at the mouth of Loch Creran. These include the barnacle *Balanus crenatus* and numerous hydroids such as *Abietinaria filicula.*

The vicinity of the study site has been sampled extensively. Although anecdotal references to Loch Creran's fauna were published in 1887 (Smith, 1887), it was not until 1956 that the first account of the loch's benthic fauna was published (McIntyre, 1956). McIntyre's work took the form of a comparison of the faunal results obtained from a Van Veen grab, Agassiz trawl and a seabed camera with data relating to benthic megafauna being analysed. In November 1967 Loch Creran's main basins (basins 2 and 3), subtidal benthic macrofauna were qualitatively surveyed at 8 stations, using a modified Forster anchor dredge and a wide Agassiz trawl (Gage, 1972a). Shallow subtidal and intertidal infauna were sampled in 1968 from 4 stations, simply by collecting the sediment with a shovel (Gage, 1972a). This preliminary survey suggested that there was no clear differentiation between stations along the main basin. The first quantitative survey of benthic macrofauna in Loch Creran was carried out in May 1968, with two of the stations sampled during the early qualitative survey (Gage, 1972a) being resampled with a Van Veen grab (Gage, 1972b; Gage and Geekie, 1973). This study showed a diverse macrobenthic community with occasional pockets of depauperate communities (Gage and Geekie, 1973) probably due to high concentrations of decaying plant material.

A further quantitative survey was carried out in May 1969, with two shallow water transects (0 to 15 m water depth) being sampled by diver coring (Gage, 1974a,b). This survey showed that although in basins 2 and 3 many of the benthic infaunal species found in the shallower area (0 to 5 m) were also found in the deeper subtidal stations, the upper basin (basin 4) shallower station (0 m) contained brackish species not occurring in the deeper stations. These results indicated that the faunal composition in the inner basin transect correlated with temperature and salinity gradients, due to the high input of fresh water from the river Creran, whilst that of the transect in the main basin was more likely to be dependent on a complex set of parameters such as wave exposure and sediment type (Gage, 1974a). Ten sublittoral sites and one littoral site from Loch Creran were surveyed by divers in June 1998 and the results, consisting of a description of the 11 biotopes encountered, presented in a Nature Conservancy Council report (Connor, 1990). More recent quantitative macrobenthic surveys were carried out in the main basin with the aim of assessing the environmental impact from the local fish cages and alginate factory (Pereira 1997, (Pereira *et al.*, 2004). A specific feature of Loch Creran macrobenthic fauna is the presence of dense aggregations of the serpulid polychaete *Serpula vermicularis*. These aggregations, or reefs, are found in both basins within the 1-13 m depth range (Moore, 1996; Moore *et al*., 1998).

As part of a study on bioturbation rates, Nickell *et al*. (2003) performed a series of *in situ* experiments on the seabed roughly 800 m east of the present study site, measuring irrigation rates of the benthos along an organic enrichment gradient.

3.5. Marine mammals; seals, cetaceans, otters

The European otter *Lutra lutra* and the common seal *Phoca vitulina* are present in Loch Creran.

Loch Creran is not an important location for the common seal and it occurs in low numbers (the SMRU survey in 2000 found only 67 individuals present at that time). Cetaceans are infrequent visitors in the Loch.

Otters are classed as Annex II species according to the Habitats Directive and have been protected in the UK from 1981 by the Wildlife and Countryside Act, and the species is identified as 'globally threatened' by the UK Biodiversity Action Plan. Otters are resident all year round and utilize the loch shores for foraging activities. Otters are highly adaptable opportunistic predators and the presence of fish farms in their territory is not known to impact on their behaviour. Scottish Sea Farms do not consider the otter to pose a threat to caged fish, and there has been no evidence of otters predating on farmed salmon in Loch Creran.

3.6. Birds

The current aquaculture activities at Loch Creran are not considered to impact on the resident or migratory bird populations.

The only important birds listed in the Creran area (Glasdrum Woods) are the song thrush *Turdus philomelos* and the spotted flycatcher *Muscicapa striata*, which are part of the local Biodiversity Action Plan. Neither species is known to have any interactions with aquaculture facilities.

Oystercatchers *Haematopus ostralegus* are considered a pest by oyster farmers, and are known to interact with these aquaculture facilities in Loch Creran; these birds are protected, however, and no action is taken against them. Eider ducks *Somateria mollissima* are a common predator on farmed mussels; visual and audio scaring devices are a common deterrent to eiders feeding on mussel lines. Shooting of eiders is prohibited unless a special license is issued after showing that all other means of control have failed.

3.7. Fisheries and wild fish populations.

Norway lobsters (*Nephrops norvegicus*) and queen scallops (*Aequipecten opercularis*) are fished immediately outside farm lease area.

There is an important local wild salmonid fishery based in Southern Linnhe/Creran system. The interactions that can occur between farmed and wild stock stem from the transmission of disease and genetic impacts through escaping farmed fish. Cooperative management of the loch is instigated through Area Management Agreements, involving other farmers (trout and salmon), river fishery managers, and freshwater salmon farming interests. Working under the direction of the Tripartite Working Group Concordat and Report (2000), the AMA aims to 'develop and promote the implementation of measures for the restoration and maintenance of healthy stocks of wild and farmed fish including:

- Environmental standards and husbandry practices.
- The availability and implementation of effective medicinal lice treatments,
- Fallowing and rotational strategies,
- Location of sites

Integral within the AMA is a escapes and recapture policy, a common sea lice management policy, vaccination policy, wild stocking disclosure, and synchronous production cycles.

Any escapes are notified immediately to SEERAD and the Creran District Salmon Fisheries Board and Fishery Trust.

3.8. Noise

The closest residential property is 509 m away. All feeders and equipment are noise insulated. Activities on site are adjusted to ensure operations are as unobtrusive as possible.

3.9. Transport

The site is accessed by boat on a daily basis, operating out of the Marine Resource Centre, Barcaldine. Harvest fish are transferred to the South Shian processing plant by well-boat.

3.10. Socio-economic impact

The farm directly employs 6 full time staff and, within the company, indirectly employs shore based staff including managers and processors. Externally the farm contributes to employment in several local and national supply industries

4. Results of ECASA field studies: Indicators and Models applied and evaluated.

4.1. Background to field programme: dates, staff, boats, stations sampled.

On 6 August 2006 H Thetmeyer (IFM-GEOMAR) deployed the chlorophyll bioassay array at a series of stations at the Creran study site from RV *Seol Mara*. On 8 and 10 August 2006, TD Nickell and S Magill (SAMS) and H Thetmeyer (IFM-GEOMAR) conducted the benthic sampling from RV *Seol Mara*, using van Veen grabs to collect sediment for the following indicators: macrobenthos; redox; particle size analysis; organic carbon; Loss On Ignition; and total organic phosphate. On 17 August 2006 TD Nickell and S McKinlay (SAMS) deployed the SAMS megacorer from RV *Calanus* for paramaterization of biogeochemical models being developed by UoV and SAMS. These models require indicators of sulphates, pore water nutrients ammonium and nitrate, dissolved iron, dissolved manganese and water content at sediment depth intervals of 1 cm from the surface down to 10 cm depth.

4.2. Sampling methods and materials, analytical methods.

All sampling (benthic macrofauna, redox, chlorophyll bioassay) was performed as per the ECASA book of protocols. Sediment organic matter (LOI), CHN, particle size and total organic phosphate (TOP) are or were analysed likewise in accordance with ECASA protocols.

Samples for paramaterization of biogeochemical modelling were collected from *RV* Calanus using a Bowers & Connelly megacorer (ϕ = 100 mm) (Barnett et al., 1984). Cores were placed in stands and kept under running seawater until returned to the laboratory. Each 10 cm long sediment core was sliced into 1 cm layers in a glove bag under nitrogen and maintained at 4 ˚C, in order to obtain high resolution data for each chemical variable. Slices were sub-sampled for solid phase (frozen at –20 ˚C) or centrifuged under nitrogen and kept refrigerated for pore water analysis.

Total (inorganic and organic) phosphorous in sediment analysis was based on the classic molybdate/ascorbic acid and spectrophotometric method described by Strickland and Parsons (1972) with modification by Aspila (1976) for use with sediments. Organic carbon (CHN) samples were lyophilised, ground and acidified to remove inorganic carbon (Tung and Tanner, 2003) prior to analysis by LECO CHN-900 auto analyser (LECO Corporation, St. Joseph, MI, USA).

For pore water sulphate determination, aliquots of the samples were diluted 100x and sulphate measured on a Dionex System 14 ion chromatograph (Dionex Corporation, Sunnyvale, CA USA) with an AG4A guard column, an AS4A separator column and suppressed conductivity detection. A calibration line was constructed using known concentrations of a standard sulphate solution, from which the concentrations of the samples was determined (S.M. Harvey, pers. comm.).

Iron and manganese concentrations in pore water were determined using a PE 4300DV Inductively Coupled Plasma-Atomic Emission Spectrometer (Perkin Elmer Life and Analytical Sciences, Inc. Waltham, MA, USA). Calibrations were prepared from commercially available single-element standard solutions (CPI International, Santa Rosa, CA, USA), and were matrix matched to sea water with respect to sodium, potassium, calcium, magnesium and strontium. Pore water solutions were diluted 20x in 5 % v/v nitric acid solution and determined in axial mode.

4.3. Benthic results

The benthic community at the cage edge was severely impacted in 2006. Only one taxon, the opportunistic polychaete *Malacoceros fuliginosa* was present represented by only 2 individuals. At the 25 m west station, 5 of the top 10 species (Table 1) were taxa considered indicative of moderately enriched conditions (Nickell et al., 1995). Further out on the west transect at the 50 m station there was only one taxon (*Scoloplos armiger*) typical of lightly enriched conditions in the top 10 (Table 1), while 5 taxa were typical of highly or moderately enriched conditions (Nickell et al., 1995). On the southern transect, the 25 m S station was dominated (Table 1) by a mixture of species typical of unimpacted areas (*Amphiura*, *Polycirrus*, *Magelona*), moderately enriched (*Pholoe*) or highly enriched conditions (*Capitella*) (Nickell et al., 1995). Similarly the 50 m S station was dominated by taxa from all of the degrees of enrichment: Normal (*Magelona*, *Amphiura*) lightly enriched (*Thyasira*, *Abra*) moderately enriched (*Melinna*, *Pholoe*) and heavily enriched (*Capitella*). Clearly this area south of the cage group was in a state of transition, with the seabed being subjected to an increasing organic loading. At the reference stations, the presence among the dominants of *Capitella* and *Melinna* suggest that the entire loch is somewhat enriched.

Table 1. The top 10 numerically dominant taxa at each station in Loch Creran in 2006 (data combined from replicate grabs).

Station	Taxon	No.	Rank	%	Cum %
0 m W	*Malacoceros fuliginosa*	2	1	100.0	100.0
25 m W	*Melinna palmata*	274	1	53.3	53.3
	Lumbrineris spp.	81	2	15.8	69.1
	Capitella sp.	19	3	3.7	72.8
	Scalibregma inflatum	16	4	3.1	75.9
	Prionospio banyulensis	12	5	2.3	78.2
	Prionospio sp.	11	6	2.1	80.4
	Glycera alba	10	7	1.9	82.3
	Magelona mirabilis	10	7	1.9	84.2
	Caulleriella alata	6	9	1.2	85.4
	Amphiura chiajei	5	10	1.0	86.4
	Eteone longa	5	10	1.0	87.4
50 m W	*Melinna palmata*	121	1	40.7	40.7
	Prionospio malmgreni	35	2	11.8	52.5
	Lumbrineris spp.	30	3	10.1	62.6
	Terebellides stroemi	12	4	4.0	66.7
	Magelona mirabilis	11	5	3.7	70.4
	Nemertea	11	5	3.7	74.1
	Capitella sp.	10	7	3.4	77.4
	Sipunculan	6	8	2.0	79.5
	Chaetozone setosa	5	9	1.7	81.1
	Scalibregma inflatum	5	9	1.7	82.8
	Scoloplos armiger	5	9	1.7	84.5
25 m S	*Amphiura chiajei*	90	1	30.3	30.3
	Melinna palmata	57	2	19.2	49.5
	Lumbrineris spp.	27	3	9.1	58.6
	Capitella sp.	14	4	4.7	63.3
	Maldanidae	14	4	4.7	68.0
	Pista cristata	11	6	3.7	71.7
	Nephtys incisa	9	7	3.0	74.7
	Pholoe inornata	9	7	3.0	77.8
	Prionospio malmgreni	9	7	3.0	80.8
	Magelona mirabilis	7	10	2.4	83.2
50 m S	*Melinna palmata*	55	1	16.0	16.0
	Amphiura chiajei	54	2	15.7	31.7
	Lumbrineris spp.	32	3	9.3	41.0
	Prionospio malmgreni	29	4	8.4	49.4
	Maldanidae	22	5	6.4	55.8
	Polycirrus spp.	15	6	4.4	60.2
	Scalibregma inflatum	15	6	4.4	64.5
	Magelona mirabilis	14	8	4.1	68.6
	Capitella sp.	13	9	3.8	72.4
	Abra alba	9	10	2.6	75.0
	Pholoe inornata	9	10	2.6	77.6
	Pista cristata	9	10	2.6	80.2
	Thyasira sp.	9	10	2.6	82.8
Ref 1	*Amphiura chiajei*	74	1	37.4	37.4
	Pista cristata	34	2	17.2	54.5
	Nephtys incisa	15	3	7.6	62.1
	Lumbrineris spp.	12	4	6.1	68.2
	Turitella communis	11	5	5.6	73.7
	Capitella sp.	8	6	4.0	77.8
	Melinna palmata	6	7	3.0	80.8
	Arctica islandica	3	8	1.5	82.3
	Maldanidae	3	8	1.5	83.8
	Myrtea spinifera	3	8	1.5	85.4
	Pholoe inornata	3	8	1.5	86.9
	Polycirrus spp.	3	8	1.5	88.4
	Sipunculan	3	8	1.5	89.9

Table 1. Cont.

Station	Taxon	No.	Rank	%	Cum %
Ref 2	*Melinna palmata*	29	1	16.3	16.3
	Amphiura chiajei	26	2	14.6	30.9
	Lumbrineris spp.	17	3	9.6	40.4
	Pista cristata	15	4	8.4	48.9
	Capitella sp.	11	5	6.2	55.1
	Sipunculan	10	6	5.6	60.7
	Golfingia sp.	9	7	5.1	65.7
	Abra alba	6	8	3.4	69.1
	Nephtys incisa	5	9	2.8	71.9
	Amphiura filiformis	4	10	2.2	74.2
	Maldanidae	4	10	2.2	76.4
	Turitella communis	4	10	2.2	78.7

Table 2. Summary data (averaged from replicates) on benthic indicators (NB: Some indices could not be calculated at Station 0 m W due to low abundance/no. of species).

	STATION						
Indicator	0 m W	25 m W	50 m W	25 m S	50 m S	Ref 1	Ref 2
N	1	257	148.5	148.5	172	99	89
S	0.5	33	26	24	28	21	20.5
Simpsons		0.69	0.81	0.85	0.92	0.82	0.89
Brillouins		1.78	2.10	2.17	2.57	1.96	2.19
Shannon		2.80	3.37	3.44	4.05	3.20	3.59
Pielou		0.56	0.72	0.75	0.84	0.73	0.85
ITI		39.09	45.96	51.09	51.76	60.76	51.85
TOC	5.18	1.01	1.26	1.16	1.03	1.58	1.92
TON	0.60	0.21	0.19	0.19	0.21	0.24	0.28
TOP	0.08	0.03	0.04	0.03	0.03	0.03	0.04
Rp	0.09	0.19	0.14	0.17	0.16	0.14	0.12
% labile OM	12.81	4.88	5.70	5.54	5.25	7.28	7.92
Redox $_{-2cm}$	-302.50	-86.50	81.00	198.00	241.50	-60.00	70.50
RPD	1					-2	-5
Distance	0	25	50	25	50	400	400
Depth	33	22	22	30	31	25	23

All of the biological indicators used describe a gradient of impact from the cage edge, and follow a classic Pearson-Rosenberg SAB model away from the source of enrichment. All of the physical indicators highlight the source of enrichment, including TOC/TON, although those indicators thereafter display a fairly flat profile across the loch and yield little information about any potential gradients. Rp and % labile OM again perform in a similar manner, while Redox$_{-2\ cm}$ seems better able to describe a gradient of enrichment.

4.4. Models used and their parameterization.

Equilibrium Concentration Enhancement (ECE) model – a box model for assessing nutrient input

The ECE model is a box model of dissolved ammoniacal nitrogen arising from farmed fish occurring within an enclosed body of water of known dimensions that is being exchanged at a steady rate (Gillibrand and Turrell (1997). Model input data include the flushing time and volume of the system, rate of excretion of ammonia by fish and consented annual production of the loch. The calculations are undertaken for basin 2 where the site is located, Creran A fish farm. This will give a more accurate prediction than using whole loch information.

The relationship between the production of fish over the growing cycle and the consented maximum biomass varies. For this model, the discharge of nutrients over a year is required, not the discharge of nutrients at a particular time (such as at peak biomass). Gillibrand et al. (2002) estimated the production for a site is approximately twice the consent biomass over a 22 month period. Thus for Creran A, consented peak biomass is 1500 tonnes (SSF) and the equivalent annual production is 1636 tonnes yr^{-1} (= (1500 tonnes*2 / 22 months) * 12 months). The equivalent figure for the whole of Loch Creran is 3000 tonnes peak biomass (Anon. 2004) and 3273 tonnes yr^{-1} production.

Table 3. Model input data for the ECE model of ammoniacal nitrogen for Loch Creran basin 2 (Gillibrand and Turrell, 1997). SSF = Scottish Sea Farms.

Symbol	Description	Model input data	Data source
V	Volume at low water	$6.7*10^7$ m^3	Calculated
A_{LW}, A_{HW}	Surface area at low water and high water respectively	5.0 km^2, 6.4 km^2	Edwards and Sharples (1985)
R	Mean tidal range (Oban)	2.4 m	Poltips software
T_f	Flushing time	2.5 days	
$Fish_{amm}$	Rate of nitrogen excretion (as ammoniacal N)	35.6 kg N $tonne^{-1}$ of fish produced yr^{-1}	cited in Gillibrand et al. (2002)
S	Nitrogen source rate (as ammoniacal N)	$1.1*10^{-9}$ kg N s^{-1} kg^{-1} caged fish	As above
M_f	Consented annual production	1636 tonnes (Creran A)[2]	SSF
Q	Steady flux of water leaving system	304 m^3 s^{-1}	

Notes
1. Mean depth at low water for all basins was used (13.4 m)
2. See text for calculation of annual production from a peak consent biomass of 1500 tonnes

The main assumptions are the excretion of ammonical nitrogen does not vary with season, temperature or feed type used across the growing cycle. The farm is assumed to be operating at the full consented annual production which is derived from peak consent biomass for Creran A, as previously described.

DEPOMOD model – a lagrangian model for predicting flux and benthic impact
DEPOMOD is a particle tracking model containing grid generation (bathymetry, cage layouts), particle tracking, resuspension and benthic impact response modules (Cromey et al., 2002).

The model was set up for Creran A fish farm with two objectives:

1. prediction of flux and benthic impact for Creran A in August 2006. The model was set up pre-survey to assist with sampling station location for the survey. Post-survey, the model predictions were refined and will be checked against benthic faunal data once available
2. prediction of flux at biogeochemical stations at Creran A, specifically for input to the BNRS model. Results of this modeling study undertaken with Daniele Brigolin of University of Venice is reported in Brigolin and Cromey (2006).

EcoWin2000 and the FARM™ model

Two more models were applied to the Loch Creran study site, aiming at two different scales:

- Ecosystem scale: an ecosystem model was developed under the EcoWin2000 (E2K) modelling platform and
- Farm scale: the FARM™ model was applied to one of the oyster aquaculture areas in Loch Creran. Specifications of each model are detailed below.

E2K makes use of an object-oriented programming (OOP) approach to implement ecological models for aquatic systems (Ferreira, 1995). The basic underlying structure is that of a spatial (1D, 2D and 3D) framework of boxes, within each of which the relevant biogeochemistry and population dynamics are resolved.

The EcoWin2000 ecological modelling platform was used to implement a research model at the ecosystem scale, simulating the major biogeochemical processes of pelagic and benthic variables as well as the seeding / harvesting features in the Loch Creran. Water and pelagic state variables were redistributed within the Loch Creran and exchanged with the ocean using the flows calculated with an hydrodynamic model – Delft3D, appropriate forcing was imposed at land and ocean boundaries for salinity, nutrients, phytoplankton and shellfish data (e.g. seeding weight, seeding densities, areas cultivated, seeding/harvesting periods, harvesting weight, etc) were integrated as parameters/variables, where applicable.

The FARM model is designed in order to determine the appropriate shellfish density for optimal carrying capacity (the greatest sustainable yield of market sized animals within a given time period) in a given farm (Ferreira et al, 2007). The FARM model allows calculating the yield of the farm based on food supply, farm size and environmental parameters. It integrates the ASSETS model, what makes it able to assess farm related eutrophication effects (including mitigation).

Model parameterization includes values for environmental conditions (water temperature, current speed, chl *a*, POM, TPM and dissolved oxygen), farm dimensions (width, length and depth) and cultivation practice (period and seeding densities).

4.5. Results

Equilibrium Concentration Enhancement (ECE) model – a box model for assessing nutrient input

Using the information in Table 3 the ECE is calculated as follows:

ECE = S * Mf / Q = 0.42 µmol l^{-1} atm N

This value of ECE can be put into perspective by (i) comparing with ECE values calculated for other Scottish sea lochs and by (ii) classifying Loch Creran basin 2 using the nutrient enhancement index which is used for locational guidelines in Scotland (Gillibrand et al. 2002) as shown in Table 4.

Table 4. ECE values for nitrogen for Scottish sea loch and classification using the Nutrient Enhancement Index. For an ECE of 0 (i.e. where no emissions from aquaculture exist, a value of 0 is assigned).

ECE (µmol l^{-1})	Number of Scottish sea lochs	Nutrient enhancement index
> 10.0	5 (4.5 %)	5
3.0 – 10.0	15 (13.5 %)	4
1.0 – 3.0	23 (20.7 %)	3
0.3 – 1.0	22 (19.8 %)	2
< 0.3	46 (41.4 %)	1
	Total 111	

Basin 2 which contains Creran A fish farm was classified with a nutrient enhancement index of 2 from the ECE value of 0.4 µmol l^{-1}. 61 % of Scottish sea lochs fall into this category or the lower category 1. A classification of category 2 for basin 2 is considered low risk in terms of eutrophication.

EcoWin2000 model

Results from the ecosystem-scale model which include watershed drivers and pressures, biodiversity, etc are useful as decision-support for licensing thresholds, agriculture inputs, stakeholder consensus, WFD and marine Strategy compliance.

Figure 6. Spatial representation of final box layout for the Loch Creran ecosystem model. Orange and blue areas correspond to aquaculture of oysters and mussels.

For the ecosystem model, 30 boxes (Figure 6) were defined for the Loch Creran study site. This model considers 3 vertical layers and has 1 ocean and 1 river inlets. Water fluxes were simulated making use of a hydrodynamic model (Delft3D – a 3D water modelling system develop by Delft Hydraulics).

FARM™ model

Results from the farm scale model, which can be driven by results of ecosystem scale models and/or by measured data, are useful for determining optimal siting, culture densities, profit maximization, eutrophication status and nutrient emissions trading and valuation.

For the application of the farm scale model, only one aquaculture area was considered in the system. The aquaculture area modelled is highlighted in Figure 6. Examples of both the ecosystem and farm models application to the Loch Creran and its results are shown below.

Water

Water residence times in Loch Creran were estimated as the e-folding time (time for the concentration in a grid cell to be reduced by a factor of 1/e, i.e., from an initial concentration of 100 % to a concentration of about 36 %) for each box defined in the ecosystem making use of the E2K model.

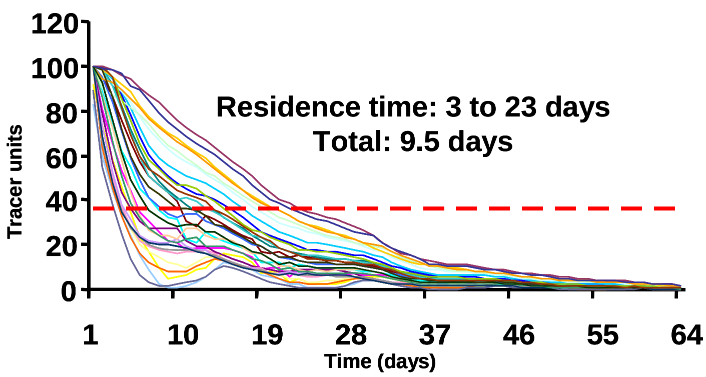

Figure 7. Estimation of e-folding time for the boxes defined in the E2K model of Loch Creran.

Residence times estimated for this system varied between 3 to 23 days. Figure 7 shows the results obtained for the water residence time estimation in Loch Creran using the E2K model.

Modelling results

EcoWin2000 model

Nutrients, phytoplankton biomass and particulate matter in Loch Creran were simulated for one year period with E2K and validated against field data obtained during the project lifetime. A subset of the simulation results and comparison with field data for the major growth drivers for shellfish growth can be seen in Figure 8 for box 1 and box 4.

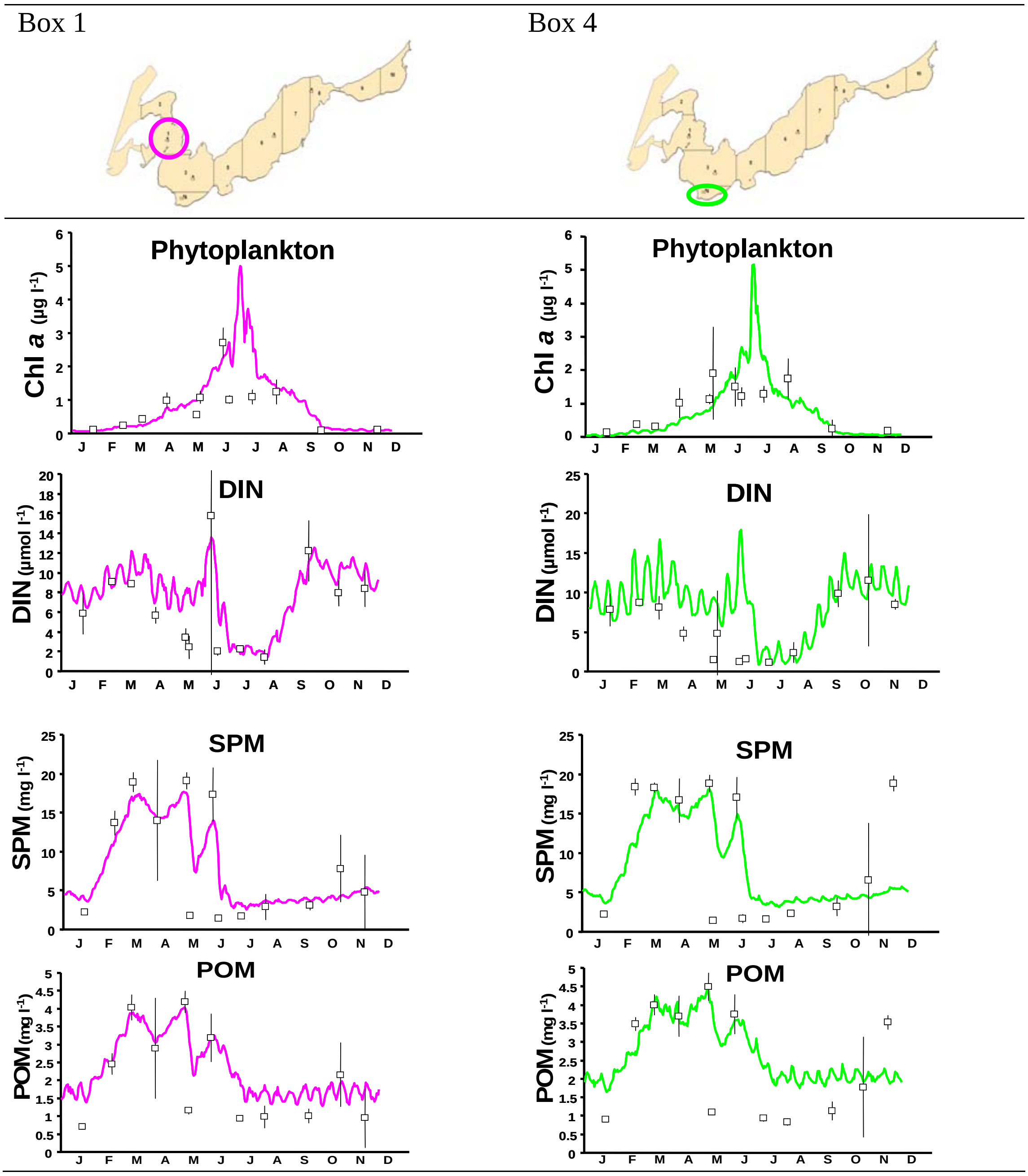

Figure 8. Results of E2K simulations of shellfish growth drivers in Loch Creran against field data. Model results are shown for one year (January – J to December – D). Lines represent model simulation and squares represent field data with standard deviation bars.

The ShellSIM individual growth model was implemented and tested within the EcoWin2000 platform. Individual length and weight were simulated for one oyster in each model box where cultivation occurs (Figure 9) and with the addition of population dynamics to the individual model, shellfish stocks over multi-year periods could be estimated (Figure 10).

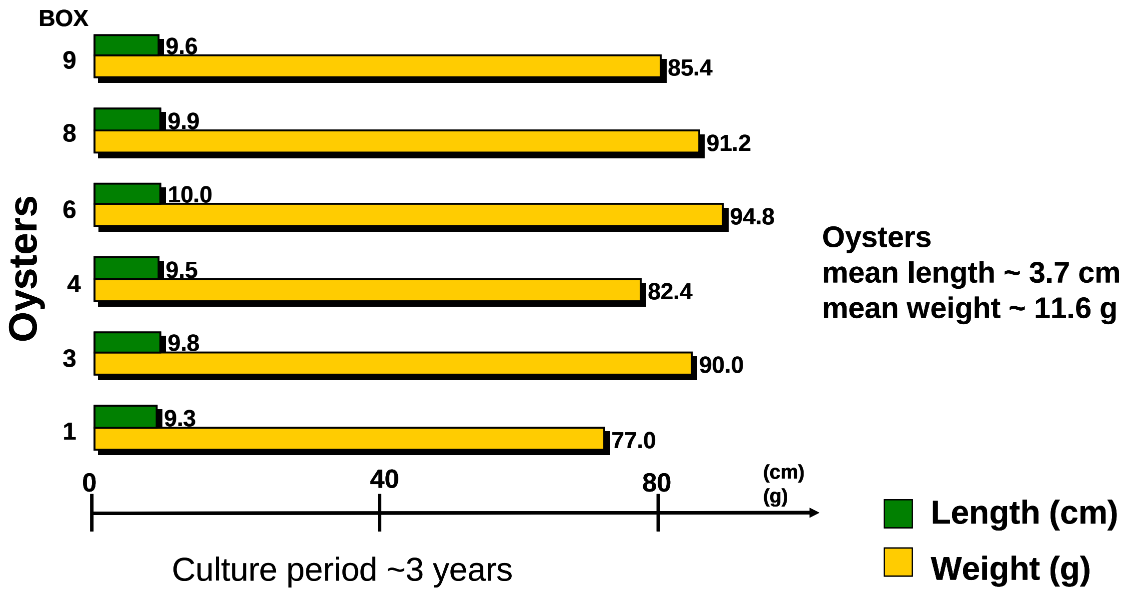

Figure 9. Individual length and weight simulated in E2K for oysters cultured in Loch Creran.

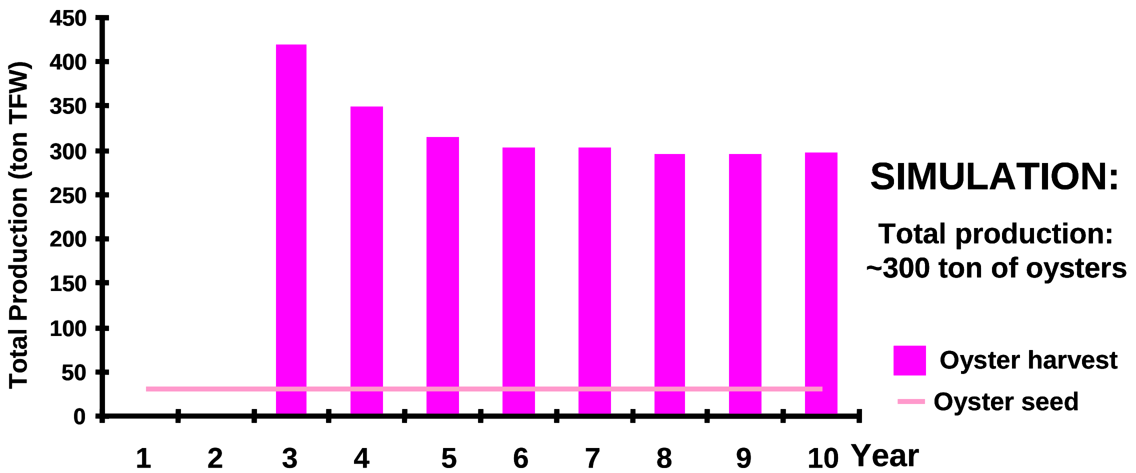

Figure 10. E2K production values simulation for Loch Creran. Model was run for a 10 year period to check for consistently stable harvesting results. Model starts stabilizing after year 6.

The total oyster production was estimated (with E2K) to be about 300 ton per year (ton y^{-1}).

The E2K model also enables to measure the ecological and economic efficiency in different parts of the ecosystem, by calculating the Average Physical Product (APP). APP is defined as the ratio between harvested biomass (Total Physical Product – TPP) and seed biomass.

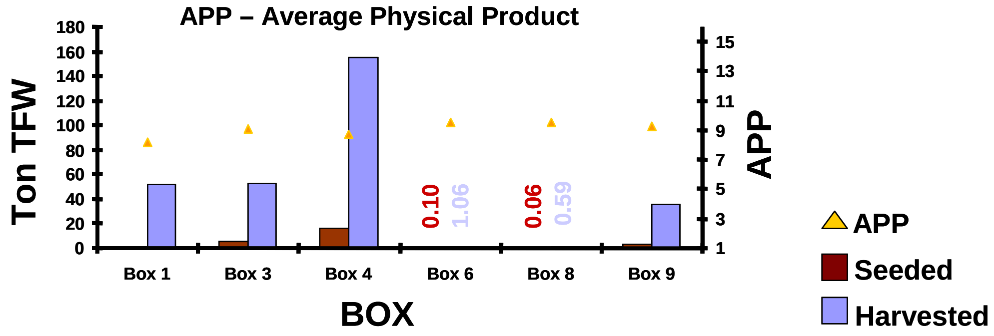

Figure 11. Model results per box for total seed biomass, TPP and APP.

FARM™ model

The FARM™ model was applied to an oyster farm in Loch Creran. E2K outputs of daily averages for salinity, water temperature, oxygen, phytoplankton biomass, suspended particulate matter and organic particulate matter were used as inputs to the FARM model. The farm layout to which the FARM model was applied is described in Figure 12. The model was run for a cultivation period of 730 days using an oyster seeding density of 50 ind m^{-2}. Integrating the ASSETS model, the FARM model is able to give outputs for eutrophication assessment regarding chlorophyll a and dissolved oxygen concentrations. Results for the eutrophication assessment are shown in Figure 13 where it can be seen that at these seeding densities, oysters would be responsible for a net removal of 2911 kg of nitrogen per year, equivalent to a sewage discharge of 882 population equivalents per year (PEQ y^{-1}).

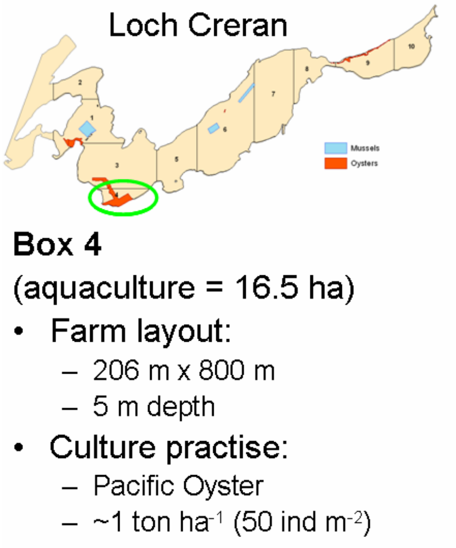

Figure 12. Description of the aquaculture area in Loch Creran where the FARM model was applied.

The ASSETS grades (which are in compliance with the Water Framework Directive) for chlorophyll and oxygen in the system are High and Good, respectively, resulting in an overall score of High.

An analysis of the interactions of the resulting TPP, APP and Marginal Physical Product (MPP – the first order derivative of the production function: TPP vs seed) is shown in Figure 14. The point of profit maximization in this system was determined for a MPP of 0.20 (MPP = Priceinput/Priceoutput), corresponding to an APP of 2.95 and a TPP of 302.5 tons of oyster total fresh weight.

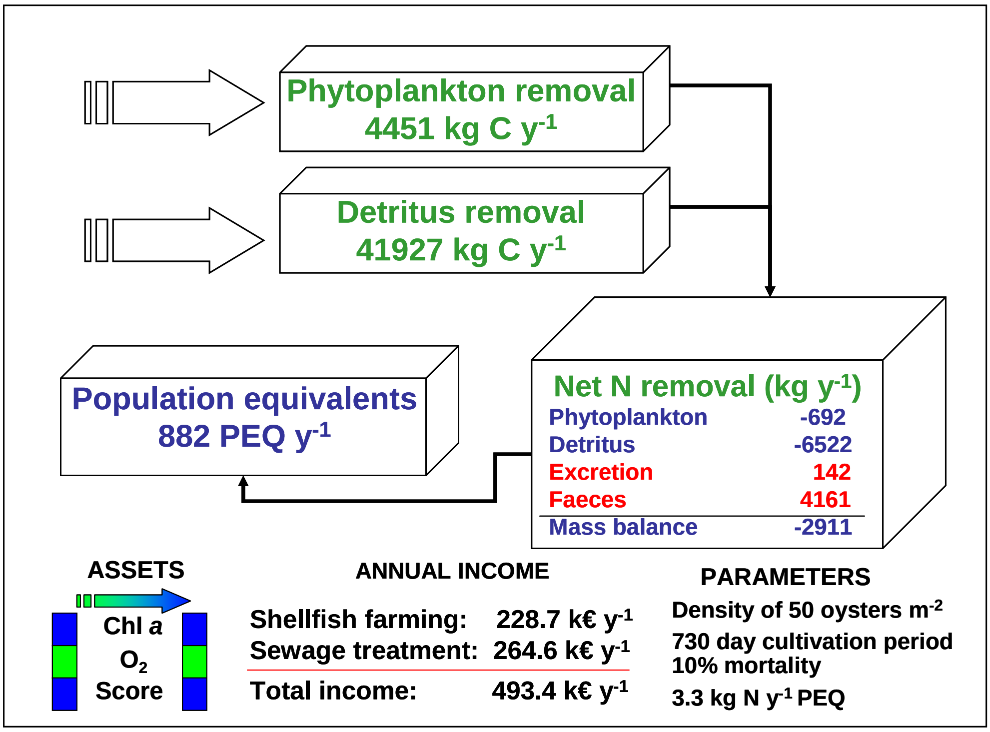

Figure 13. Mass balance and nutrient emissions trading for one oyster aquaculture in Loch Creran.

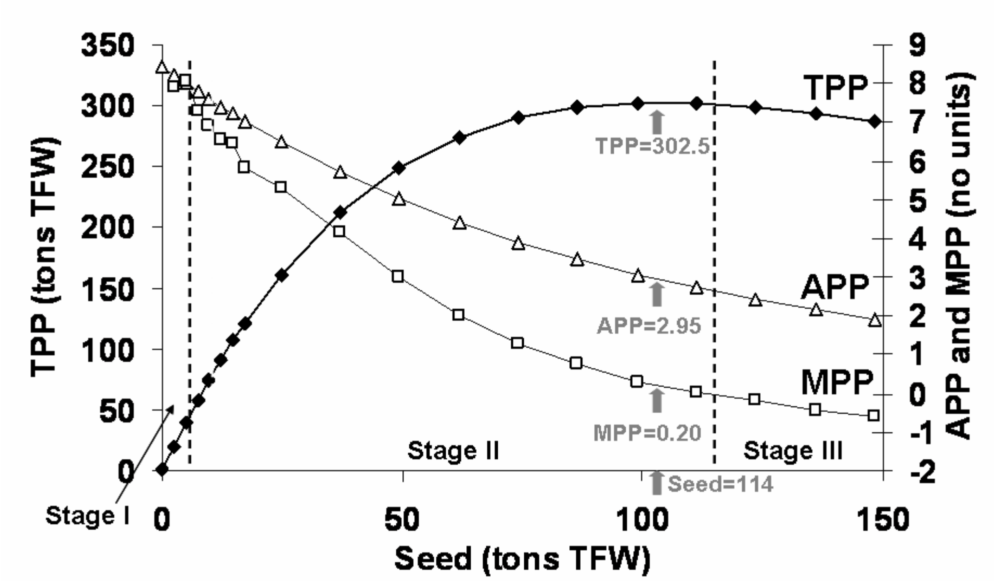

Figure 14. Economic analysis for oysters cultivated in Loch Creran with a cultivation period of 730 days.

The production scenarios run with the FARM™ model for Loch Creran considering different seeding densities are shown in Table 5.

Table 5. Production and economic parameters for different seeding densities in Loch Creran (Price of input (Pi) = 1 € kg^{-1}; Price of output Po = 5 € kg^{-1}).

Seed (ton)	TPP (ton)	APP	MPP	VMP (k€)	TR (k€)	TC (k€)	Profit (k€)
0	0	0	0	0	0	0	0
2.5	20.3	8.21	7.91	39.6	101.5	2.5	99
5	39.6	8.00	8.04	40.2	198	4.9	193
7.5	57.8	7.80	7.28	36.4	289	7.4	282
10	75.1	7.60	6.92	34.6	375.5	9.9	366
12.5	91.5	7.4	6.56	32.8	457.5	12.4	445
15	107	7.21	6.46	32.3	535	14.8	520
25	160.7	6.5	5.28	26.4	803.5	24.7	779
50	248.6	5.03	2.98	14.9	1243	49.4	1194
74	289.9	3.91	1.30	6.49	1449.5	74.2	1375
99	302.7	3.06	0.30	1.49	1513.5	98.9	1415
124	298.9	2.42	-0.15	-0.77	1494.5	123.6	1371
150	286.2	1.93	-0.58	-2.89	1431	148.3	1283

4.6. Evaluation of Indicator Performance

Discuss and evaluate (statistically as appropriate) the validity etc of the Indicators under test.

Table 6. Correlation matrix (Pearson's product-moment correlation coefficient *r*) for all univariate indicators tested in 2006. RPD = redox potential discontinuity; Rp = index of refractory OM/labile OM; TOP = organic phosphorous. Data are transformed (*S*, *N*, *Redox*$_{-2cm}$, *Distance* = log(x+1), Simpson's, *Brillouins*, *Shannon*, *Pielou*, *TON*, *Rp*, TOP = $\sqrt{x}$) where appropriate.

p>0.05

p<0.05

p<0.01

	N	*S*	*Simpsons*	*Brillouins*	*Shannon*	*Pielou*	*ITI*	*TOC*	*TON*	*TOP*	*Rp*	*% labile OM*	*Redox$_{-2cm}$*	*RPD*	*Distance*	*Depth*
N	1															
S	0.997	1														
Simpsons	0.955	0.972	1													
Brillouins	0.960	0.975	0.998	1												
Shannon	0.957	0.973	0.999	1.000	1											
Pielou	0.936	0.957	0.998	0.996	0.997	1										
ITI	0.868	0.896	0.963	0.951	0.955	0.967	1									
TOC	-0.996	-0.993	-0.960	-0.967	-0.963	-0.942	-0.884	1								
TON	-0.980	-0.977	-0.943	-0.948	-0.944	-0.924	-0.869	0.989	1							
TOP	-0.955	-0.951	-0.930	-0.937	-0.933	-0.912	-0.899	0.973	0.955	1.000						
Rp	0.852	0.812	0.676	0.697	0.685	0.636	0.546	-0.847	-0.828	-0.838	1					
% labile OM	-0.975	-0.959	-0.890	-0.906	-0.899	-0.865	-0.779	0.980	0.974	0.948	-0.918	1				
Redox$_{-2cm}$	0.965	0.978	0.996	0.998	0.997	0.993	0.943	-0.971	-0.959	-0.936	0.712	-0.916	1			
RPD	0.676	0.688	0.718	0.728	0.728	0.739	0.589	-0.629	-0.582	-0.449	0.402	-0.614	0.734	1		
Distance	0.694	0.743	0.839	0.811	0.822	0.854	0.907	-0.686	-0.656	-0.672	0.262	-0.531	0.792	0.693	1	
Depth	-0.588	-0.606	-0.548	-0.519	-0.526	-0.531	-0.474	0.531	0.547	0.385	-0.343	0.472	-0.526	-0.817	-0.621	1

From Table 6, it is apparent that most biotic indicators used in Creran correlate well with physical indicators, apart from Rp, RPD, distance and depth; Rp only correlates with N and S of the biotic indicators. RPD and depth did not correlate with any other indicator, while distance correlated with Simpsons, Brillouins, Shannon, Pielou and ITI. Physical indicators TOC, TON, TOP and % labile OM correlated with all biotic indices in Creran, thereby justifying their inclusion as indicators.

4.7. Evaluation of Model Performance

Discuss and evaluate (statistically as appropriate) the validity etc of the models under test.

EcoWin2000 model

Validation of the E2K results for shellfish growth drivers in Loch Creran are shown in Figure 8. The E2K results used in this validation are highly dependent on the boundary conditions for the river/ocean end-members and the water fluxes between boxes, which are set in this model following the results from the hydrodynamic model applied to the system. Simulated growth drivers, as phytoplankton biomass and dissolved inorganic nitrogen seem to be largely within the standard deviation bars of field data, though e.g. the phytoplankton results show a bloom during the year, which was not catch in the field data. Differences between simulated results and field data might be due to the fact that not many data was available for the river boundary of the model.

Final production results obtained from E2K can only be validated against production records. The E2K results presented here are in compliance with the typical production figures for the last years in the Loch Creran.

FARM™ model

FARM model results can only be validated if data on production for each different aquaculture site is known. There are no direct field measures that can be used to validate this model results.

5. Acknowledgements

John Rea and Sally Davies, Scottish Sea Farms, South Shian, Connel, By Oban. PA37 1SB.

6. References

Anon., 2004. Locational Guidelines for the Authorisation of Marine Fish Farms in Scottish Waters: Category 1, 2 and 3 areas designated on the basis of FRS predictive models to estimate environmental sensitivity of sea lochs. Fisheries Research Services, Aberdeen, 26 pp.

Aspila, K.I., Agemain, H., Chau, A., 1976. A semi-automated method for the determination of inorganic, organic and total phosphorus in sediments. Analyst, 101 187-197.

Black, K.D., Hughes, D.J., Provost, P.G. and Paula M. F. Pereira, P.M.F. 2000. Broad scale survey and mapping of seabed biota in Loch Creran, Argyll. Scottish Natural Heritage Commissioned Report F98AA408.

Barnett, P.R.O., Watson, J., Connelly, D., 1984. A multiple corer for taking virtually undisturbed samples from shelf, bathyal and abyssal sediments. Oceanologica Acta, 7, 399-408.

Connor, D.W. 1990 Survey of Lochs Linnhe, Creran and Aline. Nature Conservation Council, CSD Report 1073 (MNCR/SR/012).

Connor, D.W., Dalkin, M.J., Hill, T.O., Holt, R.H.F and Sanderson, W.G. 1997 Marine Nature Conservation Review: marine biotope classification for Britain and Ireland. 2. Sublittoral Biotopes. Version 97.06. JNCC Report 26.

Edwards, A. and Sharples, F. 1985 Scottish sea lochs: a catalogue. *SMBA Internal Report* 134, 110 pp.

Ferreira, J.G., 1995. EcoWin - An object-oriented ecological model for aquatic ecosystems. Ecol. Mod. 79, 21-34.

Ferreira, J.G., Hawkins, A.J.S., Bricker, S.b., 2007. Management of productivity, environmental effects and profitability of shellfish aquaculture – the Farm Aquaculture Resource Management (FARM) model. Aquaculture, 264, issue 1-4, 160-174.

Gage, J.D. 1972a A preliminary survey of the benthic macrofauna and sediments in Lochs Etive and Creran, sea-lochs along the West coast of Scotland. *Journal of the Marine Biological Association UK* 52 237-276.

Gage, J.D. 1972b Community structure of the benthos in Scottish sea-lochs. *Marine Biology* 14 281-297.

Gage, J.D. 1974a Shallow-water zonation of sea-loch benthos and its relation to hydrographic and other physical features. *Journal of the Marine Biology Association UK* 54 223-249.

Gage, J.D. 1974b Listing of putative and identified species from transect sampling by divers in Lochs Etive and Creran, and in Lochnell bay. *SMBA Internal Reports* 2 11 pp.

Gage, J.D. and Geekie, A.D. 1973 Community structure of the benthos in Scottish sea-lochs. II. Spatial pattern. *Marine Biology* 19 41-53.

McIntyre, A. 1956 The use of trawl, grab and camera in estimating marine benthos. *Journal of the Marine Biological Association UK* 35 419-430.

Moore, C. 1996 The distribution of serpulid reefs in Loch Creran, Argyll. Scottish Natural Heritage, Survey and Monitoring Report 53.

Moore, C.G., Saunders, G.R. and Harries, D.B. 1998 The status and ecology of reefs of *Serpula vermicularis* L. (Polychaeta: Serpulidae) in Scotland. *Aquatic Conservation: Marine and Freshwater Ecosystems* 8 645-656.

Nickell, L.A., Black, K.D., Hughes, D.J., Overnell, J., Brand, T., Nickell, T.D., Breuer, E. & Harvey, S.M., 2003. Bioturbation, sediment fluxes and benthic community structure around a salmon cage farm in Loch Creran, Scotland. *Journal of Experimental Marine Biology and Ecology*, 285: 221-233.

Pereira, P.M.F. 1997 Macrobenthic succession and changes in sediment biogeochemistry following marine fish farming, Ph.D thesis, University of Stirling: 135pp.

Pereira, P. M. F., Black, K. D., McLusky, D. S. and Nickell, T. D. (2004). Recovery of sediments after cessation of marine fish farm production. *Aquaculture* **235,** 315-330.

SEAS. 1991 *Report to Golden Sea Produce*. Clyde River Purification Board.

SEPA. 1992 An assessment of the impact of fish farming activities to the waters and sediments of Loch Creran, cage group A. Clyde River Purification Board.

SEPA. 1994 Environmental monitoring report to CRPB on samples taken at Creran A. Clyde River Purification Board Report.

Smith, A. W. 1887. Loch Creran notes from the West Highlands. Paisley, pp 322, cited in Moore (1996).

Strickland J., Parsons T., 1972. A practical handbook of seawater analysis. Bulletin 167 Fisheries Research Board of Canada, Ottawa. 311 pp.

Tung, J.W.T., Tanner, P.A., 2003. Instrumental determination of organic carbon in marine sediments. Marine Chemistry 80, 161-170.

7. Appendix 1

Environmental policy of Scottish Sea Farms

At Scottish Sea Farms we are committed to sustainable production and the continuous improvement of our performance to reduce and eliminate environmental impacts and achieve the highest standards of welfare for our fish.

Our environmental policy has been put in place to protect the delicate environments in which we operate. These include Loch Creran - a site of international importance and a proposed Special Area of Conservation for reefs formed by *Serpula vermicularis*. To ensure the reefs' protection, our South Shian 'Pump Ashore' project underwent an impact assessment, which was undertaken with the guidance of Scottish Natural Heritage. The result of the assessment led to extensive modifications to the project, which included the involvement of expert contractors.

We have operated our Environmental Management System to ISO14001 standards since October 2000. Our commitment to this system has been reinforced through annual surveillance visits and re-certification in 2003.

We are committed to the following environmental objectives:

- For all operations, our environmental strategy will set leading standards for the Industry and ensure continuous and long term improvements
- Our operations will be governed by the principles of sustainable production and long term care for the environment
- We will improve the knowledge of all our employees to increase their understanding and awareness of the relationships between our activities and the environment
- Our policy will be based on achieving the highest standards of fish welfare
- Our farming activities aim to limit any possible impact to wild fish stocks
- We will conduct our operations to ensure the optimal utilisation of all natural resources and the prevention of pollution
- We will conduct our operations to ensure compliance as a minimum with all relevant legislation, Industry standards and customer codes of practice.

We have also established general and local environmental targets, with detailed action plans and monitoring programmes, with the aim of achieving continuous improvement.

Some specific key areas are identified below:

- Salmon feed suppliers contracted to only use sustainable fishmeal sources
- Overall target of zero fish escapes through effective stock management
- Lice monitoring and control to be at least as strict as National Lice Treatment Strategy guidelines (SQS), with zero gravid lice our goal.
- Aim to have all active sites participating in Area Management Agreements
- The Economic Feed Conversion Factor (EFCR) should meet targeted levels on a crop by crop basis.

This policy is subject to review as required by the ISO14001 standard.