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Mesoscale effects of aquaculture installations on benthic and epibenthic communities in four Scottish sea lochs

Eleni Mente[1,2,a], Joanna C. Martin[3], Ian Tuck[3], Konstantinos A. Kormas[2], M. Begoña Santos[4], Nick Bailey[3] and Graham J. Pierce[1]

[1] School of Biological Sciences (Zoology), University of Aberdeen, Tillydrone Av., Aberdeen, AB24 2TZ, UK
[2] School of Agricultural Sciences, Dep. Ichthyology and Aquatic Environment, Fytoko Str., GR-38446 N. Ionia Magnisias, Greece
[3] FRS Marine Laboratory, PO Box 101, Victoria Rd., Torry, Aberdeen AB11 9DB, Scotland, UK
[4] Instituto Español de Oceanografía, Centro Oceanográfico de Vigo, PO Box 1552, 36200 Vigo, Spain

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Abstract – The broad-scale effects of salmon farming on benthic and epibenthic macrofaunal communities of four Scottish sea lochs (Kishorn, Duich, Hourn and Nevis) with different aquaculture loadings were investigated based on the first benthic surveys to be undertaken in these lochs. Significant variation in the benthic communities was identified between lochs, mainly related to differences in the abundance of echinoderms and polychaetes (the dominant components of the benthic communities). Variance partitioning using partial redundancy analysis suggested that approximately 9.6% of this variation could be related to aquaculture activity in the lochs (as expressed through "production" and previously modelled "impact" levels), as compared to 20.6% attributable to measured environmental factors. Epibenthic communities were dominated by echinoderms and arthropods and there was no significant between-loch variation in epibenthic community composition. No significant differences were apparent in the benthic or epibenthic community assemblages between samples taken within 2000 m of a fish farm and those taken beyond this distance. In general, our results support previous studies suggesting a spatially limited impact of salmon culture installations on the benthos, although impacts on the aquatic food web on a wide spatial scale cannot be ruled out and the link between benthic community variation and aquaculture variables identified through variance partitioning requires further investigation.

Key words: Fish farming / Environmental impact / Benthos / Community structure / Disturbance / Sea lochs

1 Introduction

Organic enrichment of the benthic ecosystem as a consequence of the accumulation of fish feed and faeces from aquaculture has been extensively studied (Yokoyama et al. 2006; Kalantzi and Karakassis 2006; Sutherland et al. 2007; Giles 2008; Sanderson et al. 2008). Recorded effects are generally limited to the immediate vicinity of the aquaculture installations and include enhancement of oxygen uptake rates in sediment beneath fish farms, hypoxia in the water overlying the sediment, increased sulphate reduction and a highly impoverished benthic community (Tsutsumi and Kikutchi 1983; Brown et al. 1987; Pearson and Black 2001; Nickell et al. 2003; Giles 2008). Beyond the impacted area is an enriched transitional zone dominated by a high abundance of opportunistic polychaetes such as *Capitella* sp. and *Scolelepis* sp. which are indicative of a polluted environment (Brown et al. 1987; Karakassis et al. 2000, 2006). The spatial extent of the transitional zone may vary, depending on the hydrography and bathymetry of the area (Giles 2008). While early studies suggested that the transitional zone extended from 15 m to 40 m away from the cages (e.g., Brown et al. 1987; Gowen et al. 1988), more recently effects on the benthic community have been detected at distances of 150 m (Weston 1990) and 250 m (Johannessen et al. 1994). Thus, effects of aquaculture installations on benthic communities can extend a considerable distance from the cages. Furthermore, impacts on the benthos may persist for many years after the farming has ceased, especially in low energy environments such as sea lochs (Gowen et al. 1988). However, it remains unclear whether there are any detectable meso-scale effects on benthic communities, i.e. within a range of a few kilometres from fish cages.

Farming of Atlantic salmon in Scotland (UK) started in the late 1960s. The present study was carried out in four sea lochs (Kishorn, Duich, Hourn and Nevis) located in the Mallaig Fishery District on the west coast of Scotland (Fig. 1a), all of which contain salmon farms that had been active for at least 5 years prior to the study. The lochs are also fished for Norway lobster (*Nephrops norvegicus*) to varying extents. These sea

[a] Corresponding author: e.mente@abdn.ac.uk

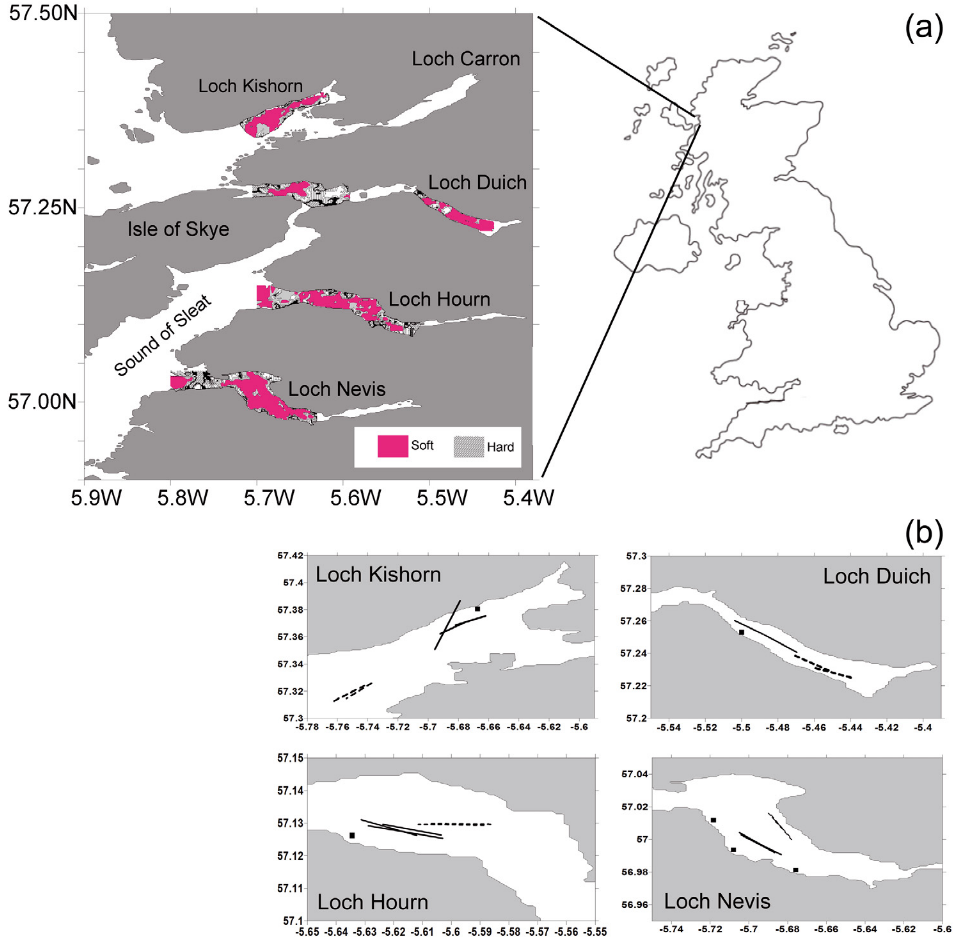

Fig. 1. a) Map and habitat map of the study area on the West Coast of Scotland and b) beam trawl tracks along which grab samples were collected (■: Fish farm, —: Trawls ⩽ 2000 m of fish farm, – –: Trawls ⩾ 2000 m of fish farm).

lochs are of glacial origin, analogous to Nordic fjords, with relatively similar physical and hydrographic characteristics. The aquaculture facilities are located in water of similar average depths (range 82–122 m) in all four lochs. There are, however, differences in flushing time (the time taken to exchange all or some part of the local water volume with new coastal water): this ranges from 3 days for loch Kishorn to 11 days for loch Hourn (see Mente et al. 2008, and references therein for a more detailed description).

Although it is difficult to obtain accurate production figures for individual fish farms, total production for each loch can be inferred from the amount of production permitted by the Scottish Environment Protection Agency (SEPA). Monitoring by SEPA is routinely carried out at fish farms and it is thought that actual production does not substantially deviate from the "SEPA consented production" (Mente et al. 2008). Loch Kishorn has the highest maximum planned production (around 4000 t y^{-1}). Loch Nevis follows with a total of 3800 t y^{-1}, the figure for loch Hourn is 2075 t y^{-1}, and loch Duich has the least planned production (1250 t y^{-1}).

The aim of this study was to examine meso-scale (km) variation in benthic and epibenthic animal communities in the four sea lochs and to determine whether there was any meso-scale effect, on these communities, of the presence or intensity of salmon culture development. Statistical analysis of the benthic and epibenthic community assemblages was carried out to identify any differences in community patterns between stations within lochs and among lochs, and to investigate the association of patterns with environmental factors and aquaculture loading.

2 Materials and methods

2.1 Sampling strategy

Sampling of benthic and epibenthic communities was undertaken on board FRV "*Clupea*", and commenced in January 2001. Five research cruises took place over three winters and two autumns, until January 2003. Two sampling transects covering similar habitats and depths were established in each loch. The first transect was positioned in "close" proximity to one or more fish farms (< 2000 m), with a second located further away from any farms (> 2000 m) (Fig. 1b). The routes of survey transects were constrained by the location of aquaculture (fish farm) and fishing (creels) within the lochs and the selection of 2 km as the cut-off distance was made primarily to ensure that a similar coverage of the "close" and "far" areas could be achieved in all four lochs. Sampling of epibenthos took place on all five cruises, while sampling of sediment and infaunal macrofauna took place only on the last three cruises.

2.2 Sediment sampling and analysis

On the cruises when sediment was sampled, five individual sediment samples were taken along each of the two transects located in each loch using a 0.1 m^2 Day Grab. The five sample points were equally spaced along the transects. Sediments were sieved through a 500 μm screen and weighed, and the fraction < 500 μm was analysed to determine particle size distribution in the range of 0.1–600 μm using a Malvern Mastersizer. The sediments were then classified according to the Wentworth scale (Wentworth 1922). Habitat (sediment type) maps were created using the approach of Greenstreet et al. (1997) with acoustic data from the "RoxAnn" system. Ground truthing using a Day Grab was carried out in each zone to confirm the output.

Sediment data were used to generate several independent indices of particle size distribution: skewness, kurtosis, median particle size and sorting coefficient. In addition, mean water depth and flushing time were obtained from data from the Marine Laboratory in Aberdeen, while aquaculture activity was expressed as aquaculture biomass and an "impact index", as described below.

Gillibrand et al. (2002) modelled the levels of nutrient enhancement and percentage areas of seabed degraded by organic carbon deposition for 111 Scottish sea lochs. Based on resulting values of the nutrient enhancement and benthic impact indices, the lochs were classified as Category 1, 2 or 3, where Category 1 is the most environmentally sensitive to further fish farming development, due to high predicted levels of nutrient enhancement and or/ benthic impact. Following Scottish Executive Locational Guidelines, lochs Duich, Hourn and Nevis are category 3 (i.e. least sensitive) while Loch Kishorn is category 2 (medium sensitivity), reflecting the higher aquaculture biomass in this loch (Gillibrand et al. 2002; Davies and Rae 2003).

A principal component analysis (PCA) was applied to the environmental parameter values to identify differences in sediment and other physical environmental characteristics among lochs and the sites within each loch.

2.3 Benthic and epibenthic organism sampling and analysis

The Day Grab sampling was also used to provide quantitative benthic macrofauna samples. The material retained by the grab was sieved through 1mm mesh sieves and the sampled specimens were fixed in formaldehyde and stored in 70% ethanol. In the laboratory, the macrofauna was sorted by hand, counted and identified to family level.

During each cruise, one 15 minute tow was made along each of the two transects in each of the lochs to collect epibenthic fauna, using a 3 m beam trawl with a 9 mm cod end. The muddy strata over which the 9 mm cod-end beam trawl was deployed often clogged the net with high amounts of anoxic mud, producing semi-solid seaweed-mud aggregations and hindering the accurate quantification of epifaunal abundance. Nevertheless, the catch was identified to species level when possible and abundance of each taxon was recorded using a scale of 1–5.

Abundance indices applied to epibenthic organisms sampled with the beam trawl.

Individuals	Index
1 = X = 5	1
5 < X = 10	2
10 < X = 50	3
50 < *X* = 100	4
100 < X	5

Non-metric multi-dimensional scaling (MDS) ordinations, using the Bray-Curtis coefficient, were carried out to display the similarities between (a) benthic and (b) epibenthic samples according to lochs, sites and environmental factors. Benthic abundance data were square-root transformed. For epibenthos, we used values of the 5-point abundance index scale and no further transformation was applied. Of the original 79 taxa of epibenthic organisms, 44 were represented by four or fewer individuals and were excluded from this analysis. There were only 28 benthic taxa (of family rank or higher) and applying the same criterion reduced this to only nine; we therefore used all taxa (but repeated the analysis with the nine more abundant taxa to confirm that this did not significantly affect the results). Community assemblages were compared by means of a "2-way crossed ANOSIM" to determine whether the dissimilarities displayed in the MDS were statistically significant. SIMPER analysis was carried out to identify the species which had most influence on the differences detected. These analyses were performed using "PRIMER" software (version 5) (see Warwick et al. 1990; Clarke and Warwick 1994a,b).

K-dominance curves, Shannon-Weiner diversity indices and species richness were calculated for both benthic epibenthic samples. Comparisons between sites were made using t-tests.

Partial redundancy analysis was used for variance partitioning, i.e. to identify the percentage of variation in the community assemblages that could be attributed to each environmental variable (Brocard et al. 1992; Zuur et al. 2007). This analysis was carried out using "Brodgar" software (www.brodgar.com).

3 Results

3.1 Habitat

The sediment in the four lochs is predominantly of 'soft' type as shown by the distribution maps and proportion composition of habitats (Fig. 1). PCA analysis on environmental variables indicates differences between the lochs, with 75% of the variation explained by the first two axes (axis 1: 50%, axis 2: 25%). Depth, sorting coefficient and median particle size (MPS) were the parameters most strongly correlated with

Table 1. Top: mean abundance of benthic individuals per phylum per m^2. Bottom: total numbers of families recorded in each phylum list.

Phylum	Stations							
	Kishorn		Duich		Hourn		Nevis	
	Close	Far	Close	Far	Close	Far	Close	Far
Mean abundance per phylum no.ind.m^{-2}								
Annelida	17.2	24.0	9.8	4.7	21.3	16.8	23.0	36.0
Arthropoda	0.7	5.3	5.7	2.0	5.3	3.3	6.5	5.3
Echinodermata	57.0	108.7	61.0	8.0	30.0	25.8	38.3	20.7
Mollusca	2.2	5.3	1.7	0.0	8.0	8.2	12.3	13.3
Other phyla	0.7	0.7	1.3	2.7	0.7	1.3	0.7	0.7
Total abundance	77.7	144.0	79.5	17.3	65.3	55.5	80.8	76.0
Number of families per phylum								
Annelida	7	5	5	4	6	5	6	7
Arthropoda	1	3	3	1	1	1	1	1
Echinodermata	2	2	1	2	1	1	2	1
Mollusca	1	1	1	0	1	1	4	2
Other phyla	1	1	2	1	1	2	0	1
Total no. of families	12	12	12	8	10	10	13	12

the first axis. The lochs thus differ in terms of sediment characteristics and depth. Lochs Hourn and Nevis have a smaller MPS and a lower sorting coefficient than Lochs Kishorn and Duich. Lochs Hourn and Nevis are also very similar in terms of depth (close site 125 m, far site 120 m and close site 91 m, far site 98 m, respectively). Skewness is highly correlated with the second axis (−0.861), and is the main explanatory variable differentiating Loch Kishorn from Loch Duich. No differences in the sediment composition between sites within each loch were identified.

3.2 Benthos

In terms of the mean abundance of individuals per phylum (Table 1), samples were dominated by echinoderms and annelids. At most stations, echinoderms accounted for at least 50% of the total abundance, mainly represented by amphiurids (Table 2). However, annelids, which were present in all lochs, included a greater diversity of families (e.g., Maldanidae, Glyceridae, Nephtyidae and Capitellidae). The arthropods were mainly represented by Axiidae, the molluscs by Nuculacea and the Cnidaria by Cerianthidae (Table 2). There were no obvious consistent differences in abundance between "near" and "far" sites within lochs.

The k-dominance curves plotted for the benthic assemblages in each loch intersected (not shown). This precludes making a comparison of the assemblages in terms of intrinsic diversity, since indices such as the Shannon-Wiener and Simpson's diversity indices cannot be relied upon to provide the same diversity ordering in such a case (Lambshead et al. 1983).

The non-metric multi-dimensional scaling (MDS) plot of the abundance of benthic families in each loch showed a clustering of the samples from Loch Kishorn (Fig. 2). No clustering of samples was apparent on the MDS plot when samples were labelled according to proximity to fish farms (not illustrated). A two-way crossed ANOSIM revealed a significant difference between lochs (global $R = 0.384$, $p = 0.001$) but no statistically significant differences between stations that were "near" and "far" from fish farms ($R = -0.071$, $p = 0.68$). Pairwise comparisons showed that Loch Kishorn was significantly different from Lochs Duich ($p = 0.04$) and Nevis ($p = 0.01$), and Loch Duich significantly different from Loch Nevis ($p = 0.02$). The dissimilarity between lochs resides in the difference in abundance of the most dominant species and not in the assemblage composition. Members of the Amphiuridae are the main species driving the dissimilarity between the lochs, in particular between Loch Kishorn and Duich (60.4%). Annelids such as the Maldanidae, Capitellidae and Nephtyidae account for much of the rest of the dissimilarity (14%–27%) between the lochs.

Variation in the species assemblages was examined in relation to three groups of explanatory variables through partial redundancy analysis. The combination of the explanatory variables examined in this study explained 46.3% of the variation in the abundance patterns. Sediment parameters were responsible for 14% of the variance, 6.6% was due to the other physical environmental variables and 9.6% was attributed to variables describing aquaculture. 16.5% of the variance was shared among the three categories, reflecting some degree of collinearity across the parameters in each category. The remaining 53.3% of the variation in the species assemblage remains unaccounted for by the available explanatory variables.

3.3 Epibenthos

Among the seven phyla encountered in the epibenthic assemblages, four (Annelida, Arthropoda, Echinodermata and Mollusca) were present at all stations. Arthropods (notably *Calocaris macandrae* and *Nephrops norvegicus*) and echinoderms (including *Brissopsis lyrifera*, *Asteronyx loveni* and *Asteria rubens*) were generally dominant in terms of mean index of abundance per haul, also the bivalve *Arctica islandica* was the most abundant species in Loch Nevis and also common in Lochs Hourn and Kishorn. In Loch Duich, cnidarians were also abundant at the close site (Table 3).

Table 2. The five most abundant families of benthic organisms at each station, ranked on the basis of mean abundance. Abundances of the same families at other stations are given in parentheses. Blank cells indicate absence.

				Duich		Hourn		Kishorn		Nevis	
Phylum	Class	Order	Family or superfamily	Close	Far	Close	Far	Close	Far	Close	Far
Cnidaria	Anthozoa	Ceriantharia	Cerianthidae	(12)	3		(10)				
Annelida	Polychaeta	Terebellida	Pectineriidae	4		(9)	(6)	(10)	(6)		
		Capitellida	Capitellidae			(9)	(7)	2	(7)	(11)	(11)
			Maldanidae	4	3	2	2	4	4	2	1
		Phyllodocida	Glyceridae	3	3	4	4	(10)	5	5	5
			Nephtyidae	(6)		(6)	(7)	3	2	(6)	(6)
		Eunicida	Eunicidae		3			(6)		(11)	(11)
Arthropoda	Crustacea	Decapoda	Axiidae	2	2	4	4	(10)	(7)	4	4
Echinodermata	Ophiuroidea	Ophiurae	Amphiuridae	1	1	1	1	1	1	1	2
	Holothuroidea	Dendrochirota	Cucumariidae		3					(11)	)
Mollusca	Bivalvia	Nuculoida	Nuculacea	(6)		3	2	5	3	3	3

List of macrobenthic families: Ampharetidae, Amphiuridae, Arenicolidae, Axiidae, Capitellidae, Cerianthidae, Cirratulidae, Cucumariidae, Cumacea, Eunicidae, Euphausiidae, Glyceridae, Golfingiidae, Hesioniidae, Littorinidae, Lucinidae, Maldanidae, Nemertean, Nephtyidae, Nereidae, Nuculoidea, Ophiuroidea, Pandalidae, Pectineridae, Scaphandridae, Spatangidae, Spionidae

Fig. 2. MDS ordination of benthic families abundances for all the samples and identified according to the loch they were taken from. Based on Bray-Curtis similarities from a square root transformation. The stress value indicates the goodness-of-fit of the regression of the distances in the MDS plot against the dissimilarities in the Bray-Curtis matrix.

The k-dominance curves for the epibenthic assemblages in each loch (not illustrated) had very similar shapes. There were no significant between-loch differences in the Shannon-Wiener indices calculated for the assemblage in each loch (p = 0.27) or in the species richness (p = 0.231) and no significant differences in diversity between sites close to and far from the fish farms in any of the lochs (2-sample t-test; Kishorn p = 0.979, Duich p = 0.897, Hourn p = 0.407, Nevis p = 0.957).

The MDS plot of the species abundances in each loch shows no clear segregation of samples (Fig. 3), and a similar result was obtained when samples were labelled according to proximity factors. A two-way crossed ANOSIM revealed no significant difference in the epibenthic assemblages between the lochs (R = 0.048, p = 0.330) or in relation to proximity to fish farms (R = −0.141, p = 0.910).

4 Discussion

4.1 *Aquaculture impacts*

Sustainable development of aquaculture requires an assessment of its environmental impacts, on both the benthic environment and the pelagic ecosystem (Black 2001). In general there is a need to monitor the environmental impacts of aquaculture using a range of parameters, at a larger spatial scale and over an extended period of time, including establishment of baseline conditions before fish farms arrived, to assess the assimilative capacity of the system and ensure that it is not exceeded.

Recent studies of environmental impacts of Scottish fish farms (e.g. Brigolin et al. 2009; Mayor et al. 2010) have focused on evaluating impacts on the benthos in the immediate

Table 3. Epibenthic species: the top five most abundant at each station based on the mean abundance index. The ranks of these species at other stations are also given in parentheses. Blank cells indicate absence.

			Duich		Hourn		Kishorn		Nevis	
Phyla	Class	Species	Close	Far	Close	Far	Close	Far	Close	Far
Cnidaria	Anthozoa	*Cerianthus lloydii*	2	(11)	(8)	(10)			(7)	4
		Urticina felina	(7)	(14)	3	(12)		(13)	(8)	4
		Funiculina quadrangularis	2	(8)	(6)	(12)				
Annelida	Polychaeta	*Sabellidae*		4		5				
		Pectinaridae	(7)	(14)	(17)	5	(13)	4	(6)	4
Arthropoda	Crustacea	*Calocaris macandreae*	1	2	2	1	(13)	3	5	4
		Munida rugosa		(14)	(8)	1		(13)	2	4
		Nephrops norvegicus	(6)	(11)	(8)	5	1	1	3	2
Echinodermata	Echinoidea	*Brissopsis lyrifera*	2	1	1	3	3	4	3	3
	Ophiuroidea	*Amphiura brachiata*	(7)	3	3	5		(13)		
		Ophiura ophiura	(7)	(14)	(6)	(22)	5		(8)	4
	Stelleroidea	*Asteria rubens*	2	(6)	(12)	(22)	5	4	(12)	(12)
		Asteronyx loveni					1	2		
Mollusca	Bivalvia	*Arctica islandica*	(7)	(11)	3	3	4	4	1	1
		Nuculacea sp.		4	(12)	(12)	(7)			
	Gastropoda	*Turritella communis*								4

List of epibenthic families: Actiniidae, Amphiuridae, Antedonidae, Aphroditidae, Arcticidae, Ascidiidae, Asteriidae, Asteronychidae, Axiidae, Brissidae, Buccinidae, Cerianthidae, Funiculinidae, Galatheidae, Glyceridae, Goneplacidae, Lucinidae, Maldanidae, Nephropidae, Nereidae, Ophiocomidae, Ophiuridae, Ophiurinae, Pandalidae, Pandalidae, Pandalidae, Pectinaridae, Polychaeta, Portunidae, Sabellidae, Sipunculidae, Turritellidae.

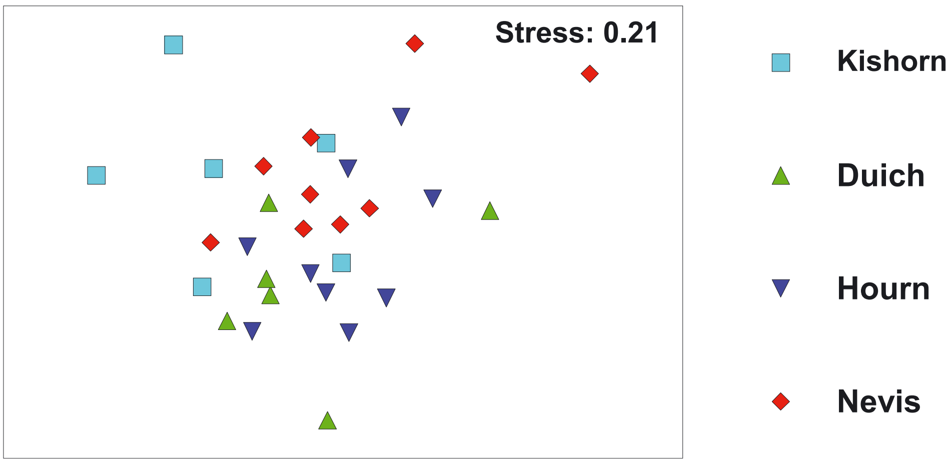

Fig. 3. MDS ordination of epibenthic species abundances for all the samples and identified according to the loch they were taken from. Based on Bray-Curtis similarities with no transformation. The stress value indicates the goodness-of-fit of the regression of the distances in the MDS plot against the dissimilarities in the Bray-Curtis matrix. In this case, the value corresponds to a useful 2- dimensional picture, though the detail should not be relied on.

vicinity of the fish farm, showing that information on local hydrography and topography, together with information on how the output of feed and faecal matter vary over the growth cycle, can be used to predict benthic impacts.

In the present study, we used two approaches in an attempt to examine evidence for larger-scale effects. Firstly, we compared the fauna along transects taken in areas less than 2000 m from fish farms and in areas more than 2 km from fish farms. If fish farms have only very localised effects we would expect no difference between the two transects. Clearly, there is an implicit assumption about scale here: effects up to 2 km distance will be apparent only if areas more than 2 km from fish farms can be viewed as controls. The second approach avoided this issue by analysing benthic community composition in relation to aquaculture loading in each sea loch.

4.2 *Loch environment*

There are 150 lochs in Scotland with a surface area above 1 km^2 and 3788 lochs over 0.04 km^2 (SEPA 1999). Edwards and Sharples (1986) have catalogued the geomorphologic features of the approximately 100 Scottish sea-lochs. Where there is no entrance sill (inlet), water will exchange freely at all depths with the open coastal sea and no irregular features associated with isolated deepwater will occur (Edwards and Griffiths 1996). However most sea lochs have at least one entrance sill, often narrow and shallow.

The hydrography and topography of the Lochs Nevis, Hourn and Duich was studied by Gowen and Ezzi (1992). The sealochs investigated in this study have relatively similar physical and hydrographic characteristics, being long, narrow and containing deep basins separated by relatively shallow sills. Compared to the other lochs in the study area, Loch Kishorn has a relatively high percentage of intertidal area. In terms of its volume, Loch Hourn is the third largest sea-loch on the Scottish West Coast and one of the deepest (185 m). These lochs have not been the subject of previous quantitative studies on benthic or epibenthic animals, although they are known to have broadly similar littoral and sub-littoral flora and fauna (Connor 1989, 1991).

4.3 *Loch benthos – composition*

More than one third of the variation in the benthic community data between lochs was explained by measured differences in the physical environment (mean depth, flushing time, sediment median particle size, sediment sorting coefficient, and sediment particle size skewness and kurtosis). Muddy sediment is characteristic of low energy environments such as these deep sea lochs with entrance sills. Incorporating other abiotic parameters (currents, turbidity, temperature and salinity), which may also influence benthic communities to a certain degree, may well have increased the percentage variation explained by environmental factors. In addition, disturbance from *Nephrops* trawling, which is carried out in all lochs, is known to disrupt benthic community stability leading to an increase in epifaunal scavengers (Tuck et al. 1998), especially echinoderms (Aronson 1990). This type of effect could also have contributed to the unaccounted variation in our analysis and may explain the dominance of echinoderms in the epibenthic samples. Loch Kishorn is the only loch with a high abundance of Capitellidae, particularly closer to the fish farm. Capitellidae are well adapted to low oxygen environments and thrive in organic-rich sulphidic sediments (Chareonpanich et al. 1994). They therefore tend to dominate in the depauperate benthic communities found close to fish farms (Pearson and Black 2001). Although Amphiuridae are the dominant benthic group at the site close to the fish farm in Loch Kishorn (indeed the “far” site in Kishorn was the only station in the present study where this family did not dominate the benthos), Capitellidae predominated amongst the polychaetes, suggesting a moderately enriched environment. The presence of capitellids at the “far” sites in Lochs Hourn, Kishorn and Nevis may signify that some wider-scale impact of aquaculture has occurred. Several authors have reviewed the use of indices for assessing the environmental quality status of a benthic system (Borja et al. 2009a). The marine biotic index (BI) (Borga et al. 2000; Muxika et al. 2005) assigns each species to an ecological grouping (GI, GII, GIII, GIV and GV) according to their sensitivity to an increasing stress gradient. The distribution of these ecological groups according to their sensitivity to pollution stress provides the BI with 8 levels from 0 to 7. In our study, for the epibenthic species the dominant ecological groups are GI and GII, although the majority of the species cannot be assigned to any ecological group because the species which we have found do not exist in Borga et al. (2000) list. Loch Kishorn is the only loch with a high abundance of Capitellidae, opportunistic species which provide a BI of level 6 and a transitional to heavy pollution benthic community. However, the sea lochs in our study could be classified as undisturbed or slightly disturbed according to their benthic community. They can change from sensitive groups (I and II) to lower successional stages (opportunistic IV and V groups) depending on the distance from the aquaculture farm. According to the European Water Framework Directive (WFD 2000/60/EC) our studied sea lochs are type NEA7, characterized as a sea loch system with 30 m depth, 4 m tidal range and flushing time in days (Borja et al. 2009a). A list of the macrobenthic and epibenthic families is given in Tables 2 and 3.

4.4 *Loch benthos – aquaculture effects*

A relatively low amount of variation in the benthic communities could be attributed to indices of aquaculture activity (9.6%) in comparison to measured natural environmental features and unexplained variation (which may include effects of other anthropogenic factors such as fishing). Another 16.5% of variation was attributable to the combined effects of environment and aquaculture. Comparison of the benthic and epibenthic community assemblages between lochs revealed no clear association between the community assemblages and the lochs’ aquaculture loadings. Although Loch Kishorn has the highest intensity of aquaculture activity, its benthic community assemblage, which differs significantly from the one in Loch Nevis, is not significantly different from the assemblage in Loch Hourn, in which the aquaculture loading is lower. The significant differences identified between the benthic communities in Lochs Kishorn, Duich and Nevis are driven mainly by variation in abundances of echinoderms and polychaetes.

Nickell et al. (2003) reported a declining trend in both macrofaunal abundance and biomass in Loch Creran was found with increasing distance from a salmon farm (up to 2000 m away from the farm) with a maximum consented farmed biomass of 1500 tonnes. Macrofaunal density 1000 m away from the farm was lower than beneath the farm cages but included species of larger individual body size which made a major contribution to the sample biomass, while macrofaunal abundance and biomass 2000 m away from the farm was very low, comprising mainly polychaetes of very small individual size.

Clearly, to some extent, the effects described above may be specific to salmon farms, However, biotic and sediment chemistry indicators from a cod farm in Vidlin Voe, Shetland (maximum consented harvest biomass 1390 t), showed that the impact on the environment up to 50 m away from the cages similar to that of a salmon farm (maximum consented harvest biomass 1500 t) of equivalent size in Loch Creran, Scotland (Nickell et al. 2009). The benthic environment was enriched at peak biomass of the cod farm, but organic carbon and nitrogen levels, and organic matter, were low and uniform. To the extent that there were differences in indicators between the two sites, these appeared to be more likely to relate to differences in the physical environment than the differences between feedstuffs used or fish excretion.

A study assessing the effects of aquaculture on marine communities by Borja et al. (2009) found that the impact from organic enrichment on benthic macrofauna extended 50 m horizontally from the farms, with fairly consistent responses seen in two composite indices (the infaunal trophic index (ITI) and AZTI's marine biotic index (AMBI) but contradictory responses in several other indicators (individual abundance, biomass). Environmental and aquaculture variables together explained 53.2% of the variability in the macrofaunal variables (individual abundance, species richness, diversity). Of these variables**,** "hydrography" (depth, distance to farm, average current speed) explained 11.5% of the variance, "sediment" (sediment redox Eh and percentages of silt and total organic matter) explained 5.4%; and (iii) "cages" (years of production and annual production) explained 15.2%. The shared variance explained by interactions among these groups was 21.1%. Because of the way the variables were grouped, it is difficult to identify the proportion of variation due to aquaculture, but it is not less than 15.2%.

A meta-analysis of data on benthic effects from fish farming by Kalantzi and Karakassis (2006) showed that several factors, including latitude, depth, sediment-type and management practices, affect the severity and spatial extent of benthic impacts. Most geochemical variables shown consistent patterns along the benthic enrichment gradient (decreasing organic material and O_2 consumption, increasing redox potential and oxygen concentration, with increasing distance from the farm). Deeper water is associated with improved waste dispersion (thus increasing redox potential, dissolved O_2 and benthic diversity) while also being associated with a higher proportion of fine sediment particles and lower macrofaunal biomass. Latitudinal trends may have a variety of underlying causes including differences in the species being farmed. In general, the horizontal extent of impacts of fish farm wastes decreases with greater depth, lower latitude and finer sediment. The type of sediment beneath the farm is a major factor determining both the extent and the severity of the impacts. Away from a farm, as organic material flux and oxygen demand decreases, animal communities return to background conditions, typified by higher species diversity and functionality (Gowen and Bradbury 1987; Nickell et al. 2003).

Kutti et al. (2007) found that large-scale impacts of a Norwegian salmon farm on benthic fauna at a deepwater site in a Norwegian fjord were restricted to a range of around 250 m. However, several indices (total abundance, biomass, and species richness) indicated changes in the structure of the benthic at distances up to 900 m from the farm and the MDS ordination revealed effects of enrichment as far as 3 km from the farm. The study showed that it is possible to maintain a high level of salmon production at deepwater sites without substantial accumulation of organic matter. Conversely however, the study suggests that, at deep sites, organic waste affects benthos on a spatial scale much larger than at shallow water sites

4.5 *Epibenthos*

Investigation of variation in the benthic and epibenthic communities in relation to the proximity of salmon farms revealed no statistically significant difference in community assemblages between samples taken within 2000 m of a fish farm and those taken further away. In general, impacts are likely to be more difficult to detect for larger and more mobile species, so the absence of differences in epibenthos between near and far sites is not unexpected given the absence differences in the benthic communities.

Local impacts on epibenthic fauna have been demonstrated for mussel culture. D'Amours et al. (2008) found that total epibenthic macrofauna abundance was generally greater in the immediate vicinity of a mussel farm (< 50 m) than at distances of 100, 500 and 2000 m from the farm. This increase in abundance probably reflected the attraction of mobile fauna due to increased food supply and possibly to the creation of a more heterogeneous habitat.

4.6 *Sampling issues*

Our results are generally consistent with most previous studies, suggesting a spatially limited impact of aquaculture installations on the benthos. Nevertheless, the sampling design used here was constrained both by cost (more replicates would have been desirable) and by the need to avoid fishing over the locations of fixed commercial fishing gear. It would have been preferable to be able to sample stations located at a range of distances from fish farms, to look for gradients or discontinuities in faunal composition. The constraints experienced in the present study are likely to be common to many areas where fish farming and fishing coexist, certainly on the west coast of Scotland. One solution may be to work with local fishermen so that sampling can take place at a time when fixed gears are not being deployed.

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References

Aronson R. B., 1990, Onshore-offshore patterns of human fishing activity. Palaios 5, 88-93.

Black K.D., 2001, Environmental impacts of aquaculture. Sheffield Academic Press, Sheffield, UK.

Borga A., Franco J., Perez V., 2000, A marine biotic index to establish the ecological quality of soft-bottom benthos within European estuarine and coastal environments. Mar. Pollut. Bull. 40, 1100-1114.

Borja Á. Rodríguez J.G., Black K., Bodoy A., Emblow C., Fernandes T.F., Forte J., Karakassis I., Muxika I., Nickell T.D., Papageorgiou N., Pranovi F., Sevastou K., Tomassetti P., Angel D., 2009, Assessing the suitability of a range of benthic indices in the evaluation of environmental impact of fin and shellfish aquaculture located in sites across Europe. Aquaculture 293, 231-240.

Borja A. Miles A., Occhipinti-Ambrogi A., Berg T., 2009, Current status of macroinvertebrate methods used for assessing the quality of European marine waters: implementing the Water Framework Directive. Hydrobiologia 633, 181-196.

Brigolin D., Pastres R., Nickell T.D., Cromey C.J., Aguilera D.R., Regnier P., 2009. Modelling the impact of aquaculture on early diagenetic processes in sea loch sediments. Mar. Ecol. Prog. Ser. 388, 63-80.

Brocard D., Legendre P., Drapeau P., 1992, Partialling out the spatial component of ecological variation. Ecology 73, 1045-1055.

Brown R.J., Gowen R.J., McLusky D.S., 1987, The effect of salmon farming on the benthos of a Scottish sea loch. J. Exp. Mar. Biol. Ecol. 109, 39-51.

Chareonpanich C., Montani S., Tsutsumi H., Nakamura H., 1994, Estimation of oxygen comsumption of a deposit–feeding polychaete, *Capitella* sp. Fish. Sci. 60, 249-251.

Clarke K.R., Warwick R.M., 1994a, Changes in marine communities: an approach to statistical analysis and interpretation. National Environment Research Council, UK.

Clarke K.R., Warwick R.M., 1994b, Similarity-based testing for community pattern: the 2-way layout with no replication. Mar. Biol. 118, 167-176.

Connor D.W., 1989, Survey of Loch Duich, Loch Long and Loch Alsh. Nature Conservancy Council, CSD Rep. No.977 (Marine Nature Conservation Review Report MNCR/SR/010).

Connor D.W., 1991, Benthic marine ecosystems in Great Britain. A review of current knowledge. Clyde sea, West Scotland, Outer Hebrides and North West Scotland. (MNCR Coastal sectors 12 to15). Nature Conservancy Council, CSD Report. No 1175 (Marine Nature Conservation Review Report MNCR/SR/011).

D'Amours O., Archambault P., McKindsey C.W., Johnson L.E., 2008, Local enhancement of epibenthic macrofauna by aquaculture activities. Mar. Ecol. Prog. Ser. 371, 73-84.

Davies I.M., Rae G., 2003, Study for research into aquaculture fish carrying capacity of GB coastal waters. FRS, Aberdeen.

Edwards A., Griffiths C., 1996, Fish farms and the physical environment in West Scotland. In: Black K.D. (ed.) Aquaculture and sea lochs. The Scottish Association for Marine Science, Oban, pp. 40-50.

Edwards A., Sharples F., 1986, Scottish sea lochs: a catalogue. Edinburgh, Scotland: Nature Conservancy Council.

Findlay R.H., Watling L., Mayer L.M., 1995, Environmental impact of salmon net-pen culture on marine benthic communities in Maine: a case study. Estuaries 18, 145-179.

Giles H., 2008, Using Bayesian networks to examine consistent trends in fish farm benthic impact studies. Aquaculture 274, 181-195.

Gillibrand P.A., Gubbins M.J., Greathead C., Davies I.M., 2002, Scottish executive locational guidelines for fish farming: predicted levels of nutrient enhancement and benthic impact. Scottish Fisheries Research Report. No. 63.

Gowen R.J., Bradbury N.B., 1987, The ecological impact of salmonid farming in coastal waters: a review. Oceanogr. Mar. Biol. Ann. Rev. 25, 563-575.

Gowen R.J., Brown J.R., Bradbury N.B., McLusky D.S., 1988, Investigations into benthic enrichment, hypernutrification and eutrophication associated with mariculture in Scottish coastal waters (1984-1988). Dept. Biological Science, The University of Stirling.

Gowen R.J., Ezzi I.A., 1992, Assessment and prediction of the potential for hypernitrification and eutrophication associated with cage culture of salmonids in Scottish coastal waters. Dunstaffnage Marine Lab. Oban Scotland and NERC.

Greenstreet S.P.R., Tuck I.D., Grewar G.N., Armstrong E., Reid D.G., Wright P.J., 1997, An assessment of the acoustic survey technique, RoxAnn, as a means of mapping seabed habitat. ICES J. Mar. Sci. 54, 939-959.

Johannessen P., Botnen,H., Tvedten O., 1994, Macrobenthos: before, during and after a fish farm. Aquac. Fish. Manage. 25, 55-66.

Karakassis I., Tsapakis M., Hatziyanni E., Papadopoulou K.N., Plaiti W., 2000, Impact of cage farming of fish on the seabed in three Mediterranean coastal areas. ICES J. Mar. Sci. 57, 1462-1471.

Kalantzi I., Karakassis I., 2006, Benthic impacts of fish farming: Meta-analysis of community and geochemical data. Mar. Pollut. Bull. 52, 484-493.

Karakassis I., Machias A., Pitta P., Papadopoulou K.N. Smith C.J., Apostolaki E.T., Giannoulaki M., Koutsoubas D., Somarakis S., 2006, Cross-community congruence of patterns in a marine ecosystem: Do the parts reflect the whole? Mar. Ecol. Prog. Ser. 310, 47-54.

Kutti T., Hansen P.K., Ervik A.,Høisæter T., Johannessen P., 2007, Effects of organic effluents from a salmon farm on a fjord system. II. Temporal and spatial patterns in infauna community composition. Aquaculture 262, 355-366.

Lambshead P.J.D., Platt H.M., Shaw K.M., 1983, The detection of differences among assemblages of marine benthic species based on an assessment of dominance and diversity. J. Nat. History 17, 859-874.

Mayor D.J., Zuur A.F., Solan M., Paton G.I., Killham K., 2010, Factors affecting benthic impacts at Scottish fish farms. Environm. Sci. Technol. 44, 2079-2084.

Mente E., Pierce G.J., Spencer N., Martin J.C., Karapanagiotidis I.T., Santos M.B., Wang J., Neofitou C., 2008, Diet of demersal fish species in relation to aquaculture development in Scottish sea lochs. Aquaculture, 277, 263-274.

Muxika I., Borja A.,Bonne W., 2005, The suitability of the marine biotic index (AMBI) to new impact sources along European coasts. Ecol. Indic. 5, 19-31.

Nickell L.A., Black K.D., Hughes D.J., Overnell J., Brand T., Nickell T.D., Breuer E., Harvey E.M., 2003, Bioturbation, sediment fluxes and benthic community structure around a salmon cage farm in Loch Creran, Scotland. J. Exp. Mar. Biol. Ecol. 285-286, 221-233.

Nickell T.D., Cromey C.J., Borja A., Black K.D., 2009, The benthic impacts of a large cod farm - Are there indicators for environmental sustainability? Aquaculture 295, 226-237.

Pearson T.H., Black K.D., 2001, The environmental impacts of marine fish cage culture. In: Black K.D. (ed.) Environmental impacts of aquaculture. Academic Press and CRC Press, Sheffield UK, pp. 1-32.

Sanderson J.C., Cromey C.J., Dring M.J., Kelly M.S., 2008, Distribution of nutrients fro seaweed cultivation around salmon cages at farm sites in north-west Scotland. Aquaculture 278, 60-68.

SEPA, 1998, Regulation and monitoring of marine cage fish farm farming in Scotland. A procedure manual. Version 1. Scottish Environmental monitoring Protection Agency, Stirling.

Sutherland T.F., Levings C.D., Petersen S.D., Poon P., Piercey B., 2007, The use of meiofauna as an indicator of benthic organic enrichment associated with salmonid aquaculture. Mar. Pollut. Bull. 54, 1249-1261.

Tsutsumi H., Kikutchi T., 1983, Benthic ecology of a small cove with seasonal oxygen depletion caused by organic pollution. Publications of the Amakusa marine Biological Lab. 7, 17-40.

Tuck I.D., Hall S.J., Robertson M.R., Armstrong E., Basford D.J., 1998, Effects of physical trawling disturbance in a previously unfished sheltered Scottish sea loch. Mar. Ecol. Prog. Ser. 162, 227-242.

Warwick R.M., Clarke K.R., Gee J.K., 1990, The effects of disturbance by soldier crabs, *Mictyris platycheles* H. Milne Edwards, on meiobenthic community structure. J. Exp. Mar. Biol. Ecol. 135, 19-33.

Wentworth C.K., 1922, A scale of grade and class terms for classic sediments. J. Geol. 30, 377-392.

Weston D.P., 1990, Quantitative examination of macrobenthic community changes along an organic gradient. Mar. Ecol. Prog. Ser. 61, 233-244.

Yokoyama H, Abo K., Ishihi Y., 2006, Quantifying aquaculture-derived organic matter in the sediment in and around a coastal fish farm using stable carbon and nitrogen isotope ratios. Aquaculture 254, 411-425.

Zuur A.F., Ieno E.N., Smith G.M., 2007, Analysing ecological data. Springer.