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Heath, M.R. and Patsch, J. and Edwards, A.C. and Turrell, W.R. and Greathead, C. and Davies, I.M. and , Fisheries Research Services (Funder) (2005) *Modelling the behaviour of nutrients in the coastal waters of Scotland - an update on inputs from Scottish aquaculture and their impact on eutrophication status.* [Report]

MODELLING THE BEHAVIOUR OF NUTRIENTS IN THE COASTAL WATERS OF SCOTLAND – AN UPDATE ON INPUTS FROM SCOTTISH AQUACULTURE AND THEIR IMPACT ON EUTROPHICATION STATUS

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November 2005

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MODELLING THE BEHAVIOUR OF NUTRIENTS IN THE COASTAL WATERS OF SCOTLAND – AN UPDATE ON INPUTS FROM SCOTTISH AQUACULTURE AND THEIR IMPACT ON EUTROPHICATION STATUS

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SUMMARY

A previous study estimated that salmon farming contributed approximately 6% of Scotland's nitrogen-nutrient input to coastal waters, and 13% of phosphorus (based on 2001 production figures). However, in some areas of the west of Scotland with small freshwater catchment areas and low levels of human habitation, aquaculture inputs represented greater than 80% of the total.

In 2002, FRS published results from an ecosystem modelling study involving a collaboration with the Institute for Marine Research, University of Hamburg, and the Macaulay Land Use Research Institute in Aberdeen, to assess the eutrophication impact of various nutrient inputs to Scottish waters. The results suggested that a 50% reduction in aquaculture salmon production would have only a small impact on water quality which would be undetectable against the background of natural variability due to climate variations.

Estimating aquaculture nutrient discharge is a difficult task. The 2002 study was based on data relating to the consented biomass of fish at farm sites in sea lochs. Since then, new data have become available on the actual harvest of fish at all sites in Scotland. In this report, we re-assess the salmon production in Scotland in 2001 and the consequent nutrient discharge, and repeat the ecosystem model runs to estimate the impact of reduction scenarios on eutrophication status.

The new data indicate that the previous study had overestimated salmon production and nutrient discharge by approximately 18% Scotland wide. Production and discharge at Shetland and in the Southern Hebrides had been under-estimated, whilst that in the Minches had been over-estimated.

New runs of the ecosystem model show that the original conclusions on eutrophication impact were sound. A scenario of 50% reduction in salmon production produced regional changes in water quality which were less than 25% of the natural variability due to climate. New runs simulating a cessation of aquaculture showed that even this extreme reduction scenario produced changes in water quality that were less than half the natural variability.

INTRODUCTION

Heath *et al.* (2002) reported on simulations of a range of eutrophication assessment criteria in Scottish shelf seas using the sc278 spatially resolved version of European Regional Seas Ecosystem Model (ERSEM; Baretta-Bekker, 1995; Baretta-Bekker and Baretta, 1997). At each grid-cell, the model simulates the annual cycles of concentration of a range of chemical and biological components of the ecosystem, driven by solar radiation, hydrodynamic conditions, suspended particulate load, river inputs, and ocean boundary data on the key state variables. The objective of the simulations was to advise on the likelihood of eutrophication effects in Scottish waters as a result of terrestrial nutrient runoff and inputs from Urban Waste Water (UWW) and Atlantic salmon aquaculture. ERSEM had previously been implemented at 60 x 60 km spatial resolution for the North Sea and the project extended the coverage to the entire Northwest European shelf from Brittany northwards, with fine spatial resolution in Scottish waters. This required the assembly of new ocean boundary, internal, initial and forcing data sets needed to run the model. Forcing data were assembled for three years (1984, 1987 and 1990) as examples of the range of climatic conditions experienced in the last few decades.

One of the major forcing data sets was the nutrient input from land sources to all of the coastal grid cells of the model. For Scotland, the OSPAR Harmonised Quantification and Reporting Procedures for Nutrients (HARP-NUT guidelines) were followed to calculate daily inputs of both inorganic and organic forms of nitrogen, phosphorus, carbon and silicon from riverine and direct discharges to the sea. The inputs were further resolved by source (urban waste water and industrial for 1999, aquaculture for 2001, and agriculture plus geological erosion for each of the three climate years). Equivalent data were compiled at monthly resolution for England, Wales, Northern Ireland, the Republic of Ireland and Norway. Continental European riverine inputs were available at daily resolution from the earlier North Sea implementation of ERSEM.

Urban waste water was found to account for approximately 12% of Scotland's nitrogen load, but 36% of the phosphorus load. Around 80% of the urban waste water load resulted from direct-to-sea discharges in 1999. The remaining 20% was discharged to river catchments. Salmon farming was estimated to contribute approximately 6% of Scotland's nitrogen input and 13% of phosphorus (based on the data available in 2001). However, in some areas of the west of Scotland with small catchment areas and low levels of human habitation, aquaculture inputs represented greater than 80% of the total.

Reference runs of the ERSEM were carried out using 1984, 1987 and 1990 meteorological forcing (transport, irradiance and agricultural plus geological nutrient inputs) together with nutrient inputs from urban waste and industrial sources set at the levels estimated for 1999, and from aquaculture in 2001. The years 1984, 1987 and 1990 were chosen specifically to represent the maximum range of climate variation in meteorological forcing. The model was then run for various scenarios of reduced nutrient load from rivers, UWW and aquaculture, and the results compared to those from the reference runs. With respect to aquaculture inputs, the model indicated that the impact of a 50% reduction in nutrient discharges from Scottish salmon farming was likely to be small (3% or less change in assessment criteria) both locally at the grid-scale of the model, and regionally. This was below the natural variability in the system in the affected areas.

Since publication of the modelling study in 2002, there has been an improvement in the availability of data on salmon production by the Scottish aquaculture industry. In this report we use the updated production data to re-assess the nutrient discharge from aquaculture and the simulated eutrophication impact thereof.

SUMMARY OF THE ERSEM CONFIGURATION

The spatial compartments (boxes) of the ERSEM sc278 version as described by Heath et al. (2002) were arranged in two layers (0-30 m and 30 m – seabed), with a horizontal arrangement as shown in Figure 1.

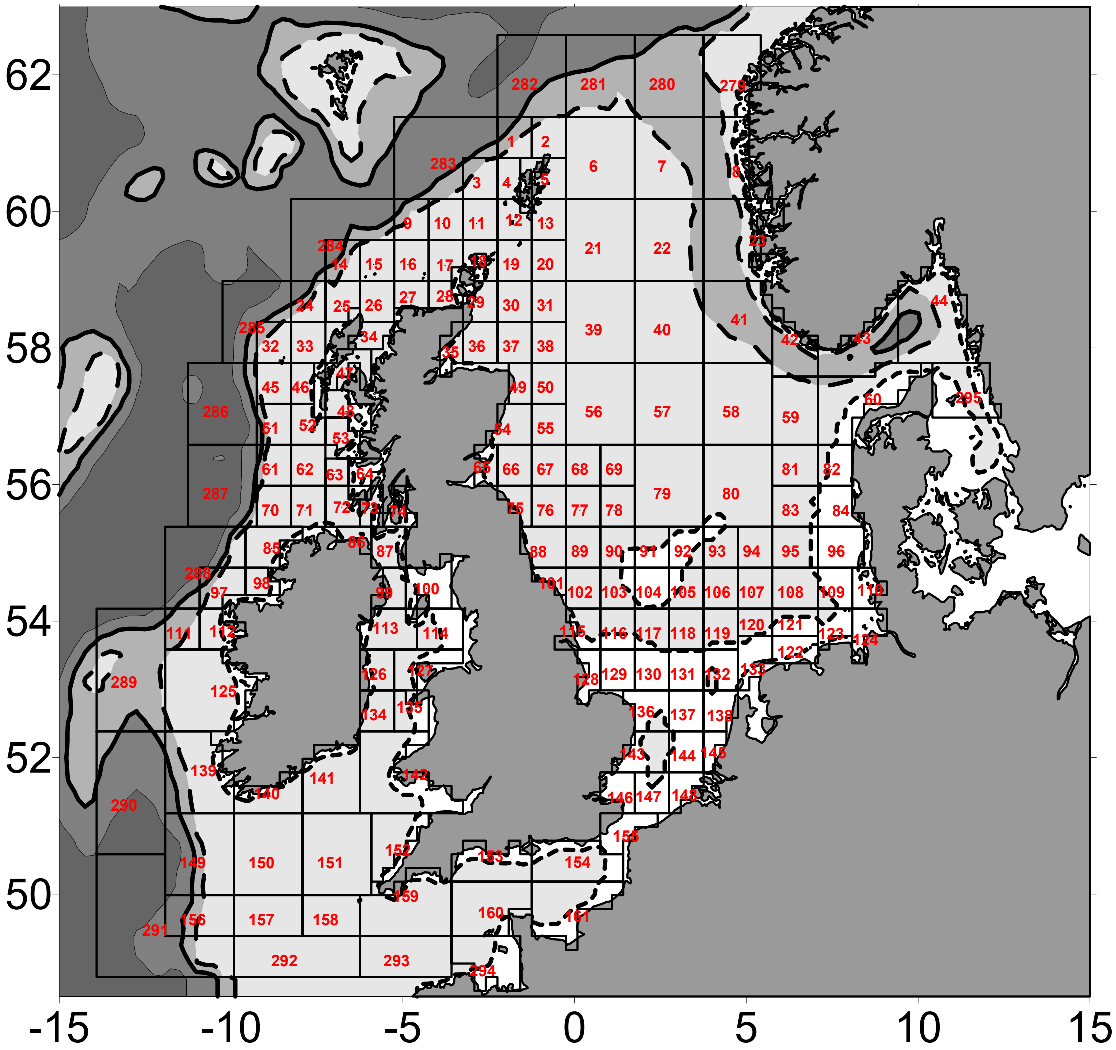

Figure 1. Configuration of boxes in the "sc278" ERSEM model, showing the upper (0-30 m) layer only.

In order to condense the model output to a manageable level of detail, 21 groups of ERSEM boxes (identified by upper layer boxes, but including the connected lower layers as well for winter nutrient criteria) were averaged for assessing the impact of nutrient loading scenarios (Table 1).

TABLE 1

Listing of the groups of ERSEM boxes forming larger assessment areas for the purposes of analysing model output.

Area	Name	Upper layer ERSEM boxes
1	Belgian coast	147, 148, 155
2	Netherlands coast	122, 132, 133, 138, 145
3	German Bight	109, 110, 123, 124
4	Danish coast	82, 84, 96
5	Skagerrak	43, 44, 60
6	Norwegian coast	8, 23, 41, 42
7	English east coast	88, 101, 102, 115, 128, 129, 136, 143, 146
8a	Scottish east coast	49, 54, 65, 66, 67, 75, 76
8b	Moray Firth	35, 36, 37
8c	Orkney Isles/north coast	17, 18, 27, 28, 29
8d	Shetland Isles	2, 4, 5, 12, 13
9a	Minches	34, 47, 48, 53
9b	Western Isles	25, 26, 33, 46, 52
9c	Southern Hebrides	63, 64, 72, 73
10a	Clyde/North Channel	74, 86, 87
10b	Eastern Irish Sea	100, 114, 127
10c	Western Irish Sea	99, 113, 126, 134, 135
11	Bristol Channel	142, 151, 152
12	English Channel	153, 154, 159, 160, 161
13	Central southern North Sea	80, 81, 83, 89, 90, 91, 92, 93, 94, 95, 103, 104, 105, 106, 107, 108, 116, 117, 118, 119, 120, 121, 130, 131, 137, 144
14	Central northern North Sea	6, 7, 19, 20, 21, 22, 30, 31, 38, 39, 40, 50, 55, 56, 57, 58, 59, 68, 69, 77, 78, 79

The combination of areas 1, 2, 3, 4, 5, 7, 8a and 13 formed the OSPAR Comprehensive Procedure Regions in the North Sea

Box 74 alone represented the OSPAR region of the Clyde.

Area 10b formed the OSPAR region in the eastern Irish Sea.

The OSPAR regions in the Bristol Channel and English Channel were contained within areas 11 and 12 respectively, but the model was not designed to investigate impacts in these regions in any detail.

The outlines of the 21 assessment areas are shown in Figure 2.

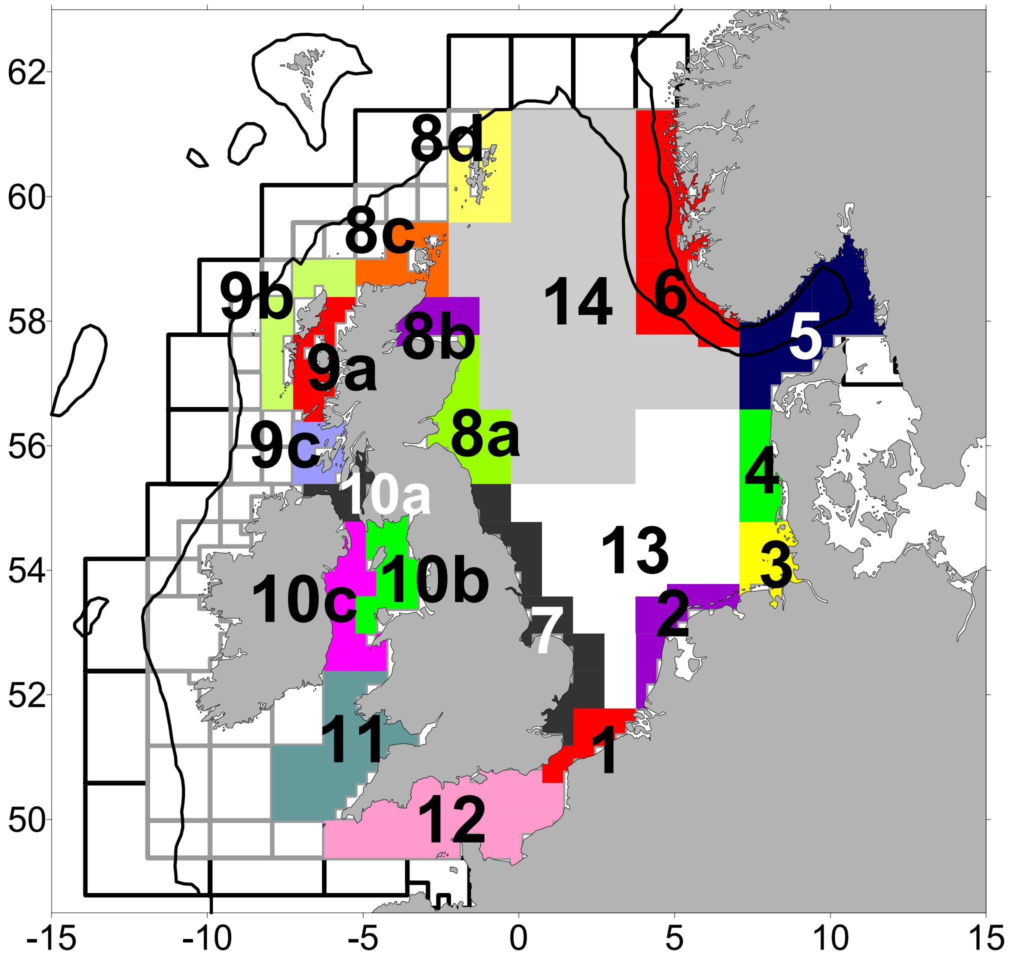

Figure 2. Outlines of the 21 asse ssment are as used to summarise the spatia l results from the ERSEM model runs.

In addition, results were examined for six individual boxes (Table 2).

TABLE 2

Individual ERSEM boxe s for which model output data was include in the eutrophication assessment.

Location	Upper layer ERSEM box
East coast	
Inverness Firth	35
Forth/Tay river plumes	65
Farne Islands	75
West coast	
Skye	47
Clyde Sea	74
Solway Firth	100

The locations of the 6 individual boxes are shown in Figure 3.

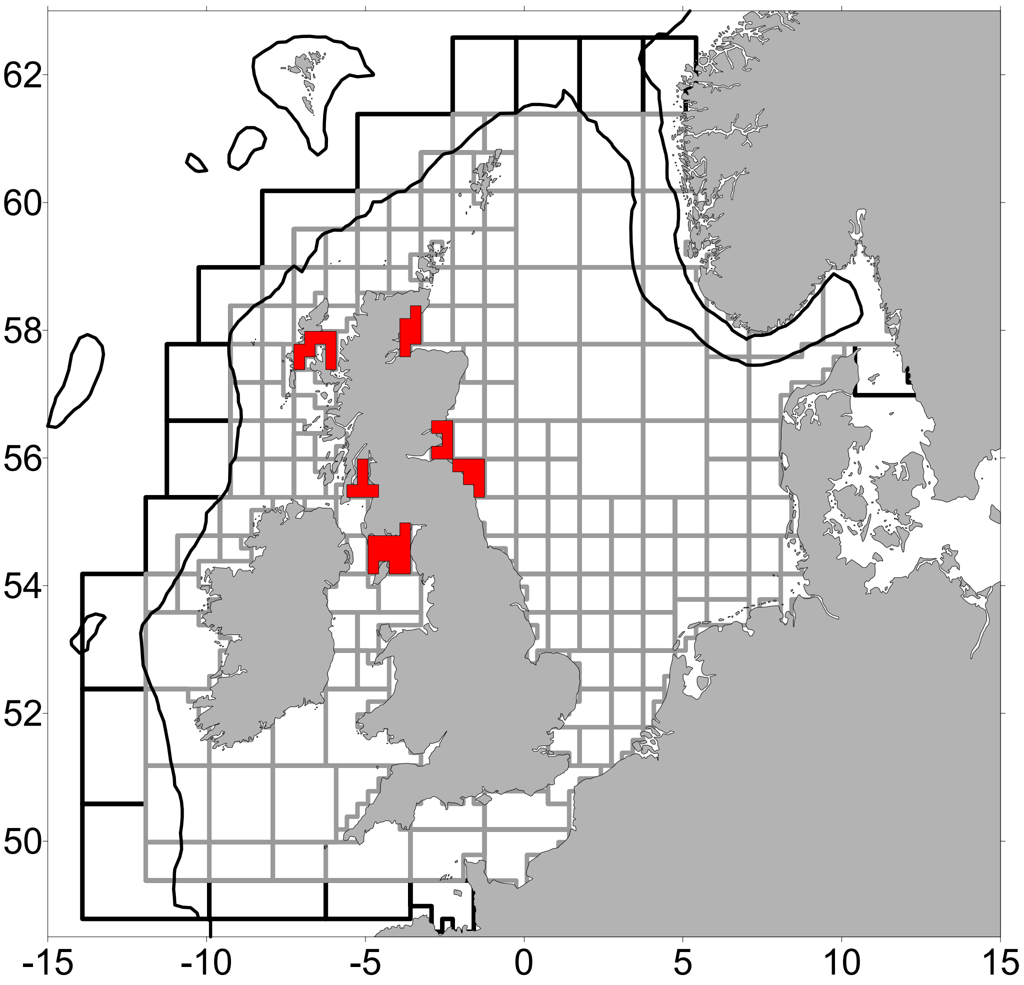

Figure 3. *Outlines of the 6 individual model cells for which ERSEM model results were extracted for each reduction scenario run.*

The various nutrient reduction scenarios analysed by Heath et al (2002) are summarised in Table 3.

For the reference runs and those representing each reduction scenario, the values of seven eutrophication assessment criteria (ASMO, 2002) were extracted from the simulation results (Table 4). These conformed to the harmonised assessment criteria adopted by ASMO. The criteria were then combined into a single 'change in water quality index (WQI)' by weighting the percentage differences between reference and reduction scenario runs (Table 4). The variation in water quality due to climate variability alone was assessed by calculating the normalised standard deviation across climate years (sd/mean) for each criterion, and combining these exactly as for the change in WQI. For each assessment area, the change in water quality due to nutrient load reduction could then be compared directly to the natural variability due to climate fluctuations alone.

TABLE 3

Summary of ERSEM nutrient reduction scenario runs reported by Heath *et al.* (2002).

Run name	Climate years	Nutrient loading
REFERENCE	1984, 1987, 1990	• 1984, 1987 and 1990 erosion and agriculture N, P, C and Si • 1999 Urban waste water N, P and C • 1999 Industrial N, P and C • 2001 Aquaculture N, P and C
UWW 75%	1984, 1987, 1990	• Urban waste water N, P and C from Scotland reduced to 25% of 1999 inputs • All other Scottish and non-Scottish inputs as reference runs
OSPAR 50%	1984, 1987, 1990	• 1984, 1987 and 1990 erosion and agriculture N and P from Scotland reduced to 50%. C and Si as reference runs • Urban waste water and industrial N, P and C from Scotland reduced to 50% of 1999 inputs • Aquaculture N, P and C from Scotland reduced to 50% of 2001 inputs. • All non-Scottish inputs as reference runs
AQUA 50%	1984, 1987, 1990	• Aquaculture N, P and C from Scotland reduced to 50% of 2001 inputs • All other Scottish and non-Scottish inputs as reference runs

TABLE 4

Weighting values applied to each of the assessment criteria in producing an overall index of water quality.

Assessment Criterion	Weighting
Winter dissolved inorganic phosphorus	0.75
Winter dissolved inorganic nitrogen	0.75
May-September average chlorophyll	1.00
Maximum weekly average chlorophyll	0.25
Annual net primary production	1.00
Maximum weekly net primary production	0.25
Diatom/flagellate ratio	-0.75

AMENDMENTS TO URBAN WASTE WATER NUTRIENT LOADING ESTIMATE

Heath *et al.* (2002) were unable to report on UWW discharges to the coastal waters around the Shetland Isles due a lack of data on volumes and concentrations of discharges from Sewage Treatment Works (STW). Since the impact of aquaculture nutrients on the status of Shetland waters was of particular concern, an alternative route to estimating UWW loading was investigated.

Based on data from SEPA (A. Rosie, pers. comm., June 2004), the population of Lerwick was assumed to be 7000, whilst the UWW nutrient load due to the fish processors, dairy and bakery plants was assumed to be equivalent to a further 18,000 persons. Similarly, the only other significant settlement on the islands (Scalloway) was taken to have a population of 812 with an additional 3188 persons equivalent load due to fish processing plants. Using the HARP-NUT guidelines (Guideline 4, OSPAR, 2000) on estimating UWW discharges for combined sewer outflows, the nutrient loading rate was then assumed to be 0.011 kg nitrogen per person equivalent per day, and 0.0018 kg phosphorus per person equivalent per day. The carbon loading was assumed to be 5.26 times the nitrogen load, based on data from STW reported by Heath *et al.* (2002). Hence the estimated loads to ERSEM box 12 (southwest Shetland) were 44, 7.2 and 321 kg of nitrogen, phosphorus and carbon respectively per day. For ERSEM box 13 (southeast Shetland) the equivalent estimates were 275, 45 and 1446 kg of nitrogen, phosphorus and carbon per day.

REVISION OF SALMON AQUACULTURE PRODUCTION DATA AND NUTRIENT DISCHARGES

The assessment of nutrient discharges from Scottish salmon aquaculture reported by Heath *et al.* (2002) was based on a simple mass balance model which estimated the proportion of nitrogen, phosphorus and carbon in fish food which was lost to the environment as excreta, faeces and uneaten material. No direct data on the usage of food were available, so food input was derived from fish production assuming a gross food conversion ratio of 1.2 (dry weight of food/wet weight of production). Production in each coastal grid cell of the ERSEM was estimated from a database of the consented biomass for each fish-farm unit, which were the only data available at that time. In fact, the database referred only to fish-farms within sealochs, and hence the assessment did not include production by units operating in open coastal waters which constitute a significant component of the total in some areas. A database of consents for these coastal sites was established in September 2002.

However, consented biomass is a rather poor indicator of production for a variety of reasons, but primarily because the consent represents the maximum allowable stock at a site, and this is not necessarily fully utilised. Therefore, data on actual harvested biomass by each fish-farm site in Scotland were compiled from annual surveys conducted by the FRS Fish Health Inspectorate. Up until summer 2004 these data had not been accessible for reasons of confidentiality. A reassessment of salmon production in 2001 was then carried out using the actual harvest data from all coastal and sea loch sites which were actively producing. Sites which used ‘pump-ashore’ water systems, or use both freshwater and sea water were excluded from the assessment. These amounted to approximately 233T of harvest in 2001. Similarly, harvest of species other than Atlantic salmon was excluded (200T in 2001).

There is a further complication in that the production cycle of Atlantic salmon in Scottish waters spans 2 years. The typical industry practice is as follows: following stocking with juveniles, the fish are grown up to a maximum biomass within one year. During the second year, fish are then progressively culled to maintain the biomass at around the maximum level. At the end of the two year period the entire remaining stock is harvested. Thus all of the harvest takes place in the second year, whilst the biological production and food input to support the harvest are spread over two. For an individual site comprising a set of synchronously stocked cages, year-specific harvest is therefore not equal to year-specific production or food input. However, assuming that at some scale of spatial aggregation the 2-year production cycles of the farms in a region become asynchronous, then regional harvest will be equal to regional production, and hence proportional to regional food input. We assumed that aggregation to the scale of the ERSEM coastal boxes was sufficient to ensure asynchrony between sites, and duly based our box-specific estimates of production on the spatially aggregated harvest data for 2001.

The estimates of salmon production during 2001 in each assessment region as quoted by Heath *et al.* (2002), and the re-assessed estimates, are shown in Table 5 and Figure 4. These clearly show that whilst the total production in Scotland was in fact lower than previously estimated by Heath *et al.* (2002), the distribution was different so that some areas were significantly lower and others were higher. In particular, whilst production in the Minches area was found to have been overestimated previously, production at Shetland and in the Southern Hebrides area had been underestimated.

TABLE 5

Salmon aquaculture production (kT y^{-1}) as estimated for 2001 by Heath *et al.* (2002), and using more up-to-date survey data in this report.

Assessment area	Salmon production in 2001 as estimated by Heath et al. (2002) (kT y^{-1})	Revised estimate of salmon production in 2001, as derived in this report (kT y^{-1})
Scottish east coast (8a)	0	0
Moray Firth (8b)	0	0
Orkneys (8c)	8,985	6,335
Shetland isles (8d)	25,574	39,745
Minches (9a)	98,767	43,723
Western Isles (9b)	16,128	9,981
Southern Hebrides (9c)	1,675	26,114
Clyde/North Channel (10a)	11,775	12,260
Scotland total	**162,904**	**138,158**

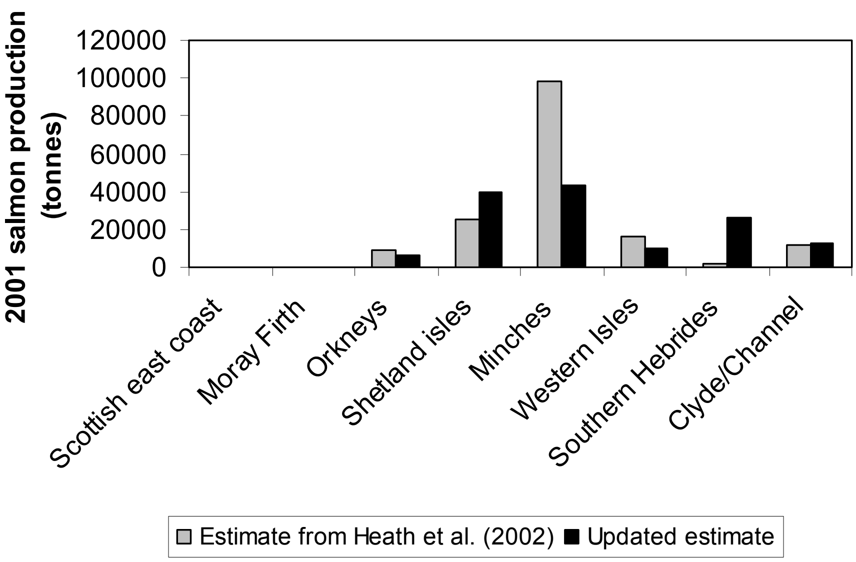

Figure 4 Comparison of aquaculture salmon production by ERSEM assessment region as estimated by Heath *et al.* (2002), and according to the re-assessment presented in this report.

Applying the salmon mass balance model as described by Heath et al. (2002) to the re-assessed production data produced a new set of nitrogen, phosphorus and carbon discharge data for Scotland (Table 6).

TABLE 6

Re-assessed values of 2001 salmon production and consequent nitrogen, phosphorus and carbon discharges for each Scottish coastal box of the ERSEM.

ERSEM box	Location	2001 salmon production (tonnes y^{-1}, wet weight)	Nitrogen discharge (tonnes y^{-1})	Phosphorus discharge (tonnes y^{-1})	Carbon discharge (tonnes y^{-1})
4	NW Shetland	5372	286.9	64.7	717.3
5	NE Shetland	25299	1351.0	304.9	3377.9
12	SW Shetland	9074	484.6	109.3	1211.5
18	NE Orkney	5213	278.4	62.8	696.0
25	NW Lewis	6032	322.1	72.7	805.4
27	Cape Wrath	747	39.9	9.0	99.7
29	SE Orkney	375	20.0	4.5	50.1
33	West Harris	3949	210.9	47.6	527.3
34	North Minch	12093	645.8	145.7	1614.6
47	Skye	20868	1114.4	251.5	2786.3
48	Small Isles	5803	309.9	69.9	774.8
53	Coll/Tiree	4959	264.8	59.8	662.1
64	Firth of Lorne	22677	1211.0	273.3	3027.8
73	Sound of Jura	3437	183.5	41.4	458.9
74	Clyde Sea	12260	654.7	147.7	1636.9
Total		**138158**	**7377.6**	**1664.8**	**18446.6**

Combining the re-assessed aquaculture nutrient loads, with the previously estimated land erosion and agriculture, industrial and urban waste inputs, plus the additional urban waste inputs from Shetland, provided a new assessment of the total nutrient discharge to Scottish coastal waters (Table 7, Figure 5).

TABLE 7

Composition of nutrient loads from Scotland as a whole. Agricultural and natural erosion inputs are given for each of the three climate years 1984, 1987 and 1990 and for the average of these three years; urban waste water and industrial inputs for 1999; and aquaculture inputs for 2001. The total figure refers to the sum of the mean agriculture and erosion input plus other discharges.

	Annual freshwater flow ($x10^6$ m^3)	Total nitrogen load (kt/year)	Total phosphorus load (kt/year)	Total carbon load (kt/year)	Total silicon load (kt/year)
1984 agri.+erosion	89.00	158.29	5.76	484.67	443.96
1987 agri.+erosion	81.43	80.45	6.36	519.01	346.49
1990 agri.+erosion	115.11	103.03	6.58	551.63	459.27
Avg. agri.+erosion	95.18	113.92	6.23	518.44	416.57
1999 Urban waste		17.94	5.16	83.42	0
1999 Industry		1.16	0.71	8.15	0
2001 Aquaculture		7.38	1.66	18.45	0
Total	**95.18**	**140.40**	**13.76**	**628.46**	**416.57**

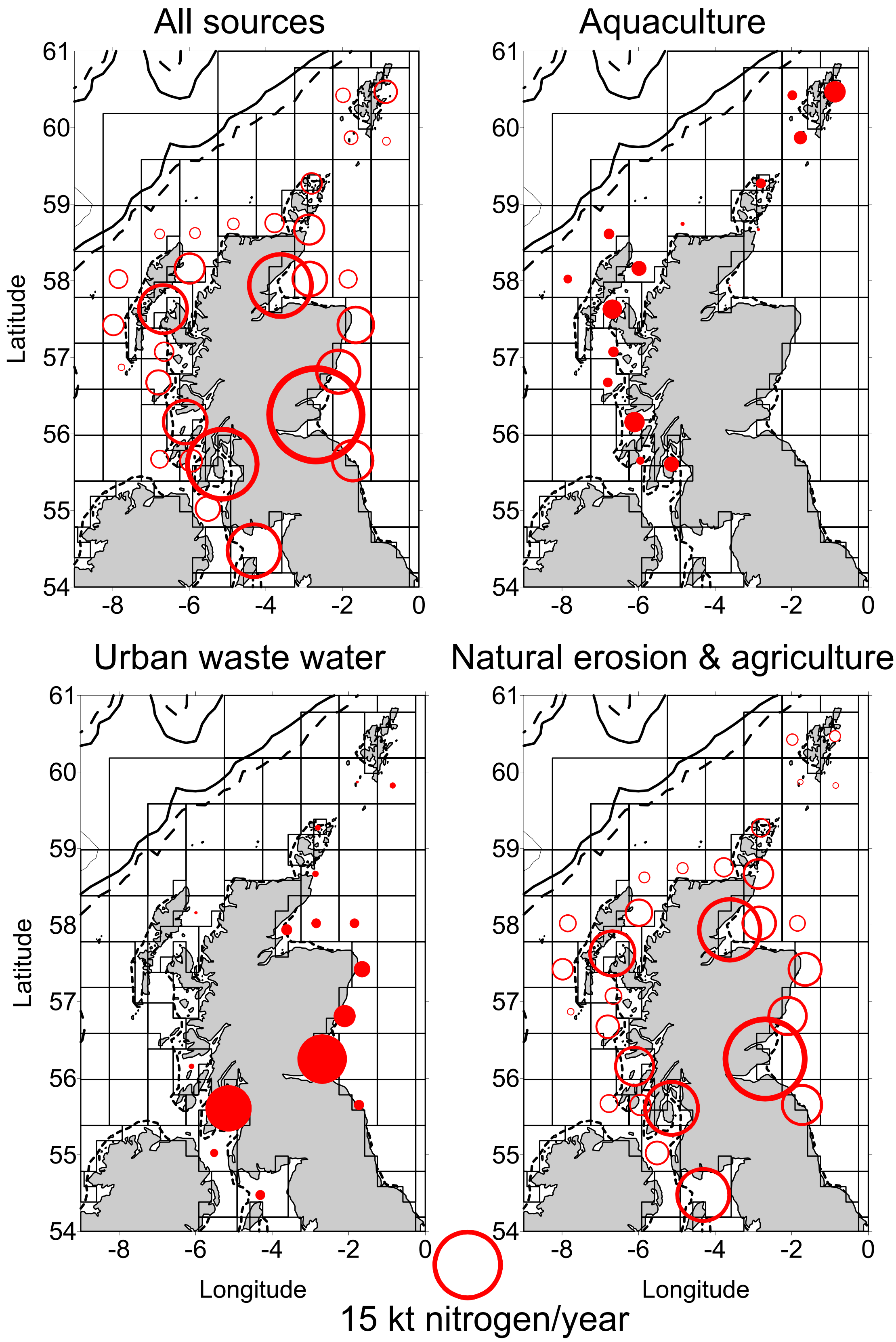

Figure 5. Spatial distribution of an nual nitrogen discharges to Scottish coastal w aters, based on agricultural and erosion inputs estimated for 1990, plus urban waste water for 1999 and aquaculture for 2001.

RESULTS FROM NEW SIMULATIONS WITH THE ERSEM

Three new reference runs of the ERSEM were carried out, one for each of the climate years 1984, 1987 and 1990, with the previous series of agricultural, erosion and industrial inputs, and the updated urban waste and aquaculture inputs. Then, two aquaculture reduction scenarios were simulated, the first replicating the 50% reduction in salmon production simulated by Heath et al. (2002), and the second representing a new scenario where all aquaculture was discontinued (100% reduction) (Table 8).

TABLE 8

Summary of ERSEM scenario runs using the re-assessed aquaculture nutrient loadings.

Run name	Climate years	Nutrient loading
REFERENCE	1984, 1987, 1990	• 1984, 1987 and 1990 erosion and agriculture N, P, C and Si • Revised 1999 Urban waste water N, P and C • 1999 Industrial N, P and C • Reassessed 2001 Aquaculture N, P and C
AQUA 50%	1984, 1987, 1990	• Aquaculture N, P and C from Scotland reduced to 50% of reassessed 2001 inputs • All other Scottish and non-Scottish inputs as reference runs
AQUA 100%	1984, 1987, 1990	• No aquaculture N, P and C inputs • All other Scottish and non-Scottish inputs as reference runs

The new reference runs differed from the previous versions only very slightly, by <0.3% in all areas except the Minches (1.1%, 1.7% in the Skye box) where the greatest adjustment of the estimates salmon production was located.

The impact of 50% reduction in aquaculture production on the eutrophication status of the assessment regions was broadly similar to that indicated by the earlier simulations. The impact in the Minches area was smaller than previously estimated, whilst that at Shetland and in the Southern Hebrides region was greater. The magnitude of the estimated impact of a 50% reduction in aquaculture production did not exceed 25% of the natural variability in eutrophication status due to climate fluctuations in any of the assessment areas (Figure 6, Table 9). The east coast of Scotland was practically unaffected by aquaculture nutrient loading due to its remoteness from the main centres of activity.

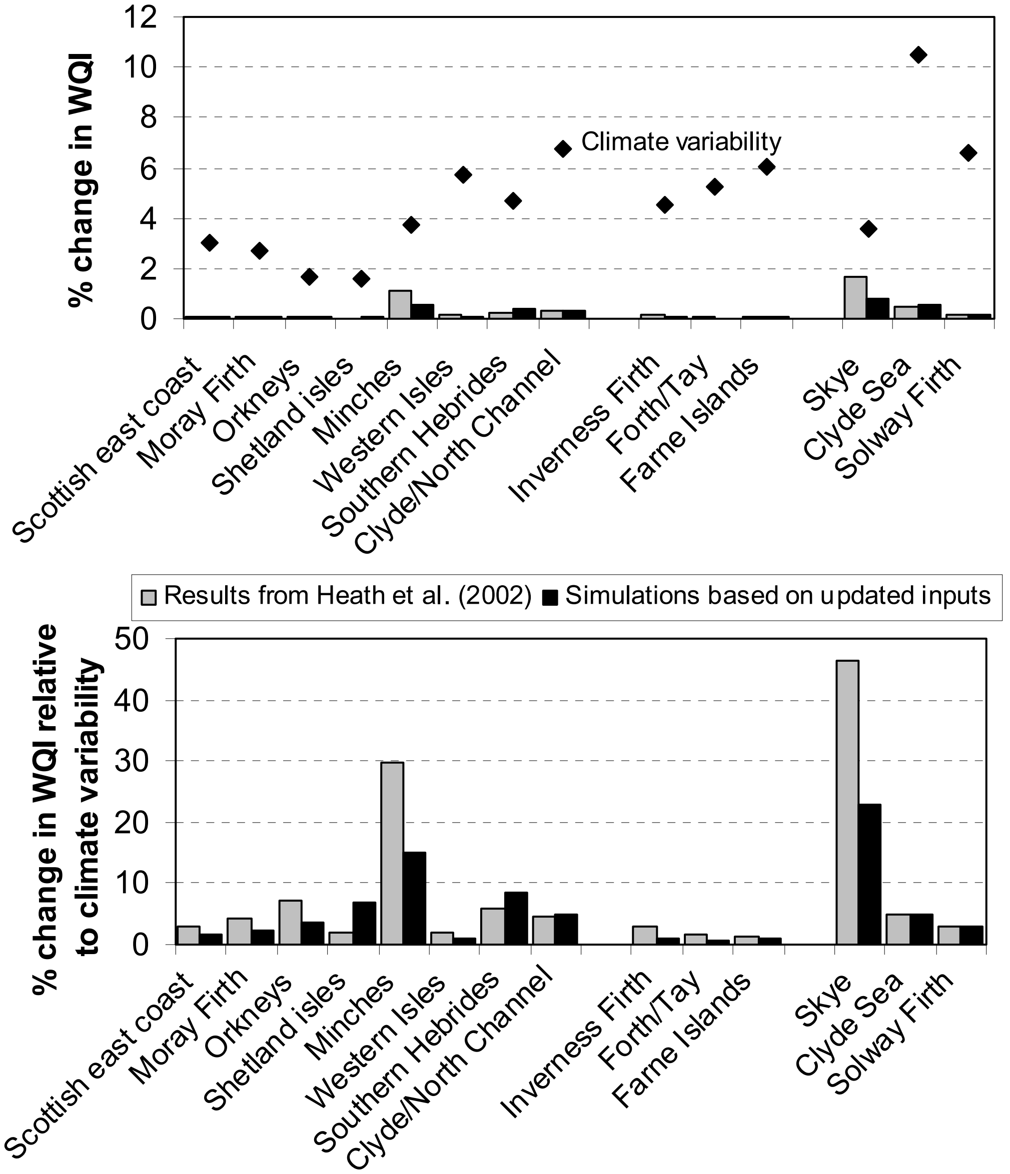

Figure 6 Percentage change in water quality index (WQI) in the Scottish assessment areas and the 6 individual ERSEM boxes, due to a 50% reduction in aquaculture production. Results from previous ERSEM simulations (reported by Heath et al. (2002)) (grey bars), and new simulations with the re-assessed nutrient loadings (black bars). Upper panel: % change compared to the % variability in the reference runs due to climate variations (symbols). Lower panel: change due to nutrient load reduction expressed as a proportion of the variability due to climate.

The impacts of a cessation of aquaculture were greatest in the Minches, Southern Hebrides and Clyde Sea areas, but still did not reach 50% of the variability in eutrophication status due to climate. The change in status due to ceasing aquaculture was small at Shetland and amounted to around 15% of the climatic variability (Figure 7, Table 9).

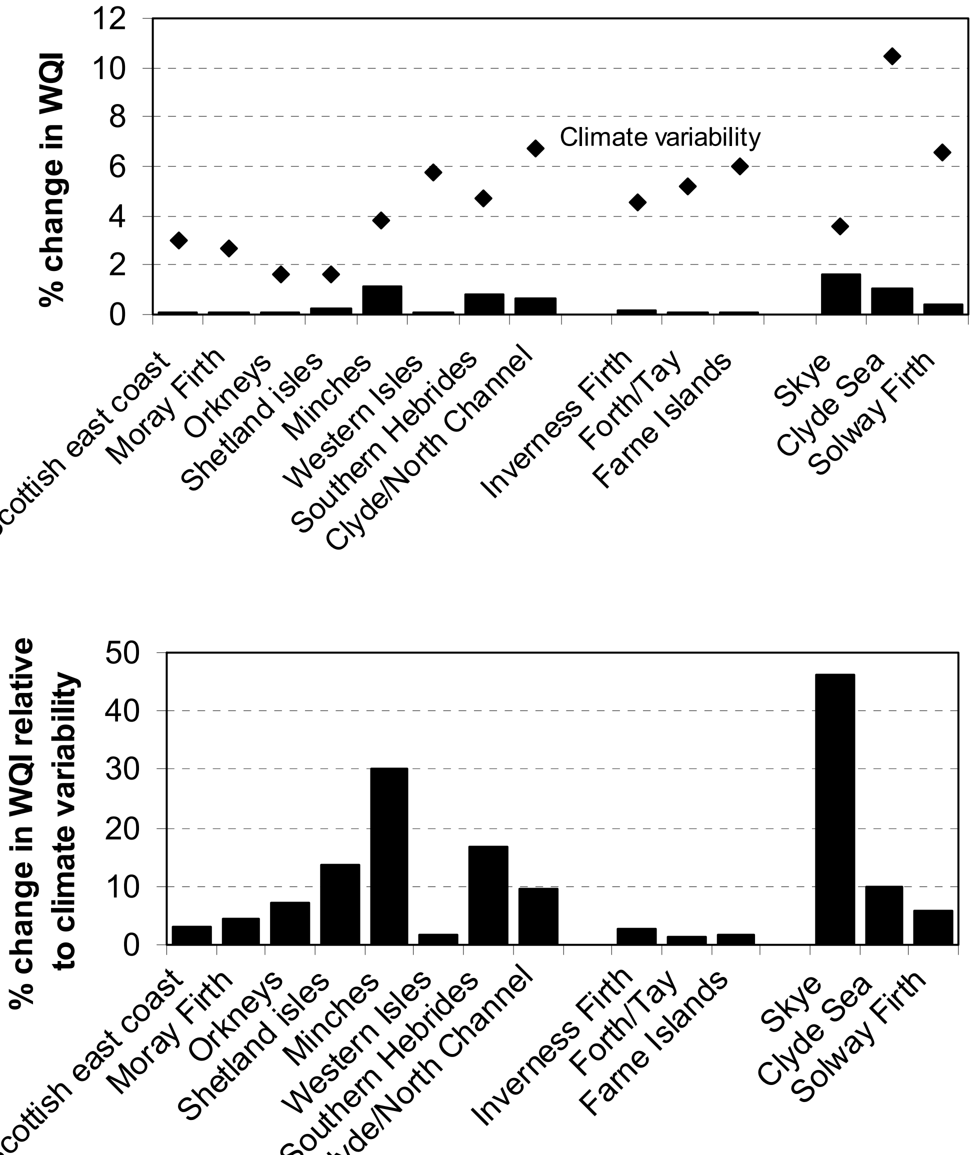

Figure 7 Percentage change in water quality index (WQI) in the Scottish assessment areas and the 6 individual ERSEM boxes, due to a 100% reduction in aquaculture production (i.e. cessation of aquaculture). Upper panel: % change compared to the % variability in the reference runs due to climate variations (symbols). Lower panel: change due to nutrient load reduction expressed as a proportion of the variability due to climate.

TABLE 9

ERSEM simulations of variability in reference run water quality due to climate variations, changes in water quality due to a 50% and 100% reduction in aquaculture production.

Assessment area/ERSEM box		Reference run climate variability (%sd/mean)	AQUA50% % change in WQI	AQUA100% % change in WQI
Assessment areas:				
8a	Scottish east coast	2.99	0.05	0.09
8b	Moray Firth	2.68	0.06	0.12
8c	Orkneys	1.64	0.06	0.12
8d	Shetland isles	1.60	0.11	0.22
9a	Minches	3.77	0.56	1.14
9b	Western Isles	5.73	0.05	0.11
9c	Southern Hebrides	4.68	0.39	0.79
10a	Clyde/North Channel	6.75	0.32	0.65
East of Scotland ERSEM boxes:				
35	Inverness Firth	4.51	0.05	0.13
65	Forth/Tay	5.22	0.03	0.07
75	Farne Islands	6.03	0.05	0.10
West of Scotland ERSEM boxes:				
47	Skye	3.58	0.82	1.65
74	Clyde Sea	10.48	0.52	1.05
100	Solway Firth	6.60	0.20	0.38

CONCLUSIONS

1. New data indicate that the assessment of Scottish salmon aquaculture production in 2001 reported by Heath et al. (2002) overestimated Scotland-wide production by approximately 18%. The new estimate of Scotland-wide production in 2001 was 138 158 tonnes. Production at Shetland and in the Southern Hebrides area was underestimated by the previously available data, whilst production in the Minches was overestimated.

2. Repeat simulations of eutrophication impact using the European Regional Seas Ecosystem Model (ERSEM) and the updated aquaculture nutrient loadings show that the conclusions of Heath et al. (2002) regarding the consequences of a 50% Scotland-wide reduction in salmon production are still sound. The change in water quality as a consequence of a 50% reduction would be less than 25% of the natural variability due to climate variations.

3. Additional simulations carried out using the updated loadings also showed that the consequences of a cessation of Scottish aquaculture would still be less than half the natural variability due to climate variations.

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