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Recovery of a sewage sludge dumping ground. II. Macrobenthic community

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ABSTRACT: Following cessation of sewage sludge disposal at a site ca 2 km from Garroch Head, Isle of Bute, Firth of Clyde (Scotland), a study of the recovery of the benthic environment was undertaken. In order to permit comparisons a reappraisal of data obtained in 1971, whilst the site was still actively in use, was undertaken. Based on the parameters used, the benthic community showed a marked recovery from its status in 1971 and now approaches what should be considered as normal for this slightly enriched area.

INTRODUCTION

Before using the sea for waste disposal its potential for recovery, particularly that of the benthic fauna, must be considered. Information on the recovery phase following sewage sludge disposal is limited to field investigations at a site off Philidelphia, USA (Devine & Simpson 1985) and extrapolation from experimental studies (Eleftheriou et al. 1982). This paper reports investigations of the recovery of the benthic environment 11 yr after cessation of dumping of sewage sludge at an accumulating disposal site in the Firth of Clyde, Scotland.

The dumping of wastes in Scottish waters is controlled under the Food and Environment Protection Act, Part II, 1987 (FEPA), formerly the Dumping at Sea Act, 1974 (DASA). A review of the practical approach taken to the assessment of applications to dispose of wastes in Scottish waters is given by Topping (1987). The legislation lays certain constraints on disposal operations, one of which is to specify the precise locations at which dumping is to take place. However, prior to the implementation of DASA this specification was not statutory and the location of the disposal operation was not well defined. Prior to 1974, the disposal operation in the Firth of Clyde was located in an area ca 4 km north of the present operation (Fig. 1). The site was situated in 70 to 80 m of water which has slow water currents (< 10 cm s^{-1}; Dooley 1979). This area received sewage sludge virtually continuously from 1904 to 1974, but not subsequently, as described by Harper & Greer (1988).

Various studies (MacKay & Topping 1970, MacKay et al. 1972, Topping & McIntyre 1972, Halcrow et al. 1973) undertaken before 1974 on the effects of the dumping operation at the northern site (Site A) showed the classical effects of organic enrichment on the benthic fauna, i.e. a decrease in species diversity and an increase in individual population abundance and biomass. Halcrow et al. (1973) also estimated that 20 km^2 of the sea bed sediment was contaminated with trace metals.

In 1985, the recovery of this area of sea bed was investigated by re-surveying the stations sampled by Topping & McIntyre (1972) for benthic community analysis and sediment trace metal concentrations. This survey was carried out using the same benthic sampling techniques, and in addition, a further 5 stations were sampled in 1985 for trace metal concentrations in the sediment. The results of the macrobenthic community studies are given in this paper, whilst the trace metal concentrations and geochemistry are presented in Rodger et al. (1991; companion paper) and Rodger & Davies (1991) respectively.

METHODS

At each station previously sampled by Topping & McIntyre (1972) (Stns 1 to 5; Fig. 1 of Rodger et al. 1991), two 0.1 m^2 van Veen grab and two Craib corer (Craib 1965) samples were taken in March 1985 from FRV 'Scotia'. At the additional stations (6 to 10) only core samples were obtained. As in 1971, the grab samples were washed through 500 µm mesh sieves and

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the residue preserved in 10 % formalin. In the laboratory, the macrofauna was extracted by hand, identified to species where possible, enumerated and weighed (blotted wet weight). From these basic data (number of species present, abundance and biomass), the Shannon-Wiener index of diversity using natural logs (Shannon & Weaver 1963) and the Heip index of evenness (Heip 1974) were calculated. Log-normal distributions were calculated using the technique devised by Gray & Mirza (1979) with the probit modification proposed by Gray & Pearson (1982). The general applicability of this descriptive model has been the subject of some debate, since many community estimates appear not to exhibit log-normal distributions. However, the data available in this study are too limited to allow the useful application of more complex analytical techniques, and the approach adopted is considered adequate for the relatively straightforward descriptive comparison made below.

One Craib core from each station (1 to 10) was analysed for redox potential using the technique outlined in Pearson & Stanley (1979). The upper 8 cm of the second core was sectioned at 1 cm intervals, and stored frozen (−20 °C) prior to trace metal analysis in the laboratory (Rodger et al. 1991, Rodger and Davies 1991). Organic carbon levels in sediments from Stns 1 to 5 were estimated by a combination of the wet ashing technique, as outlined in Strickland & Parsons (1972), with the titrimetric analysis of Menzel (1966).

RESULTS

1985 survey

Analysis of the macrobenthos from the 5 stations sampled yielded a total of 123 species/taxa (Table 1) and 4870 individuals. The number of species present ranged from 44 at Stn 3 to 64 at Stn 2, with mean densities ranging from 910 ind. m^{-2} at Stn 3 to 18145 m^{-2} at Stn 5. The mean biomass varied between 27.94 g m^{-2} at Stn 4 and 108.09 g m^{-2} at Stn 5.

The fauna at all stations was dominated by polychaetes, which accounted for a mean of 54 % of the total abundance, and 45 % of the biomass. The other elements of the fauna showed very variable contributions to the total abundances (Table 2). Up to 47 % of the total abundance at Stns 1 to 4 consisted of the top 5 species (Table 3). At Stn 5, the top 5 species grouping accounted for 81 % of the abundance, which is reflected in the depressed Shannon-Wiener diversity and Heip evenness indices in comparison with the other 4 stations (Table 4).

The log-normal distributions of the species (Fig. 1) showed good agreement between the 2 samples at each station. In 1985 samples from Stns 1 to 4 had only a few geometric classes represented and exhibited a steep slope to the line, but the absence of representatives of class VII (32 to 63 ind. m^{-2}) and class VIII (64 to 127 ind. m^{-2}) geometric groups at Stn 5 caused the data to exhibit a broken line ('dog-leg'; i.e. change of slope).

The redox profiles for Stn 1 to 10 in 1985 (Fig. 2) showed a gradation from less reducing conditions at Stns 1, 3, 4, 6, 7 and 10, to more reducing conditions, particularly at depth, at Stns 2, 5, 8 and 9. The redox potential at Stns 1, 3 and 4 did not fall below 0 mV within the top 10 cm of the cores. Where present, the redoxcline (Bagander & Niemisto 1978) was shallowest (1 to 2.5 cm) at Stns 2 and 5, and deepest (> 4 cm) at Stn 6. Stn 2 showed low redox values between 4 to 6 cm depth and Stn 8 exhibited the most reducing conditions, with a value of −230 mV at a depth of 10 cm.

The organic carbon concentrations (Fig. 3) in surface sediment (0 to 2 cm) for Stns 1 to 5 were between 2 and 3 %. At Stn 5, concentrations decreased with depth to 1.5 % at 8 cm, whilst at Stn 2 levels showed a marked increase with depth from 3 % at the surface to 5 % at 4 to 6 cm, with a slight decrease with depth thereafter to 4.5 %. Stns 1, 3 and 4 showed no significant change from surface to a depth of 8 cm.

1971 survey

In order to make comparisons between stations sampled in 1971 and 1985, it was necessary to re-analyse the original disaggregated data, which was presented in summarised form by Topping & McIntyre (1972). It should be noted that the faunal analysis of the 1971 samples was not as rigorous as that undertaken in 1985, and certain groups were not separated, e.g. Capitellidae and Cirratulidae were identified only to family level.

In 1971, a total of 48 species/taxa were found at the 5 stations sampled, with a maximum contribution of 35 species at Stn 4, and a minimum of 13 at Stn 3. Total abundances (Table 5) ranged from 3290 ind. m^{-2} at Stn 4 to 52 500 m^{-2} at Stn 3, and biomasses from 30.14 g m^{-2} (Stn 1) to 162.71 g m^{-2} (Stn 3). These values were derived from a single sample taken at each station. With the exception of Stn 4, the data from individual samples in 1985 showed consistently higher numbers of species. Similarly the total species complement in 1985 was much greater than might have been expected if duplicate samples had been taken in 1971. At Stn 4, the number of species, diversity and evenness were similar in 1971 and 1985.

The fauna in 1971 (as in 1985) was dominated by annelids. However, unlike 1985 the grouping of the top

Table 1. Species list of benthic macrofauna for the Garroch Head old dump site, Stns 1 to 5, 1985. Taxonomic order within phyla according to Howson (1987). Suffixes as per Pearson et al. (1986)

Polychaeta	
Aphrodita aculeata (juv.)	
Enipo kinbergi	
Harmothoe sp.	
Harmothoe antilopes	
Harmothoe castanea	
Pholoe inornata	
Pholoe sp.	
Phyllodoce laminosa	
Anaitides mucosa/maculata	
Dentanaitis subulifera	
Eulalia viridis	
Eteone longa	
Glycera alba	(*+)
Glycinde nordmanni	
Goniada maculata	(+)
Shaerodorum gracilis	
Gyptis roseus	
Kefersteinia cirrata	
Ophiodromus flexuosus	
Ancistrosyllis groenlandica	
Synelmis klatti	
Nereis longissima	
Nephtys cirrosa	
Nephtys hombergii	
Nephtys hystricis	
Lumbrineris fragilis	
Lumbrineris gracilis	
Lumbrineris tetraura	(*+)
Ophryotrocha hartmanni	
Eunicidae (juv.)	
Scoloplos armiger	(+)
Levensenia gracilis	
Paradoneis lyra	
Apistobranchus tullbergi	
Poecilochaetus serpens	
Minuspio cirrifera	
Prionospio malmgreni	
Pseudopolydora cf *paucibranchiata*	
Scolelepis (Parascolelepis) *tridentata*	
Spiophanes kroyeri	(*)
Chaetozone setosa	(*)
Cirriformia sp.	
Tharyx marioni	
Tharyx multibranchis	
Tharyx sp.	
Raricirrus sp.	
Diplocirrus glaucus	(+)
Capitellidae (indet)	
Capitella capitata	
Dasybranchus caducus	
Mediomastus sp.	(o)
Notomastus latericeus	
Rhodine loveni	
Ophelina acuminata	
Polyphysia crassa	(*)
Scalibregma inflatum	(*)
Myriochele oculata	
Amphictene auricoma	
Melinna cristata	
Anobothrus gracilis	
Eclysippe sp.	
Terebellidae	
Terebellides stroemi	(*)
Pista cristata	
Lysilla loveni	
Polycirrus sp.	
Jasminiera caudata	
Oligochaeta	
Tubificoides benedeni	
Oligochaete (indet.)	
Mollusca	
Chaetoderma nitidulum	
Lunatia poliana	
Cylichna cylindracea	(o)
Philine scabra	
Philine sp.	
Gastropod A	
Gastropod B	
Nucula sulcata	(*+)
Nucula tenuis	(*)
Myrtea spinifera	
Thyasira flexuosa	(o)
Tellimya ferruginosa	
Acanthocardia echinatum	
Parvicardium minimum	
Spisula sp.	
Abra sp.	
Abra alba	(*+)
Abra nitida	
Arctica sp. (juv.)	
Hiatella arctica	
Corbula gibba	(*)
Bivalve A	
Crustacea	
Balanus nauplius	
Ostracoda	
Tanaidacea	
Amphipod A	
Amphipod B	
Amphipod C	
Ampelisca sp.	
Ampelisca gibba	
Eriopisa elongata	
Cumacean A	
Iphinoe sp.	
Eudorella truncatula	
Leucon nasica	
Diastyllis lucifera	
Diastyllis rathkei	
Euphausidae	
Nephrops norvegica	
Calocaris macandraea	
Zooea	
Echinodermata	
Ophiuroidea (juv.)	
Amphiura chiajei	(+)
Amphiura filiformis	(o)
Ophiura affinis	
Others	
Priapuliae	
Nematoda	
Nemertea	
Cerianthus sp.	

(o) Listed as species having high dominance in Clyde Sea area
(*) Listed as species indicative of enrichment on the Garroch Head site
(+) Listed as species indicative of enrichment on a variety of grounds

Table 2. Summary of abundance and biomass of the benthic macrofauna at Garroch Head old dump site, Stns 1 to 5, 1985. 1 and 2 refer to samples

	Stn 1		Stn 2		Stn 3		Stn 4		Stn 5	
	1	2	1	2	1	2	1	2	1	2
Abundance (ind. m^{-2})										
Polychaeta	880	100	1 090	1 290	540	570	770	680	13 550	4 490
Oligochaeta	–	–	50	–	–	–	50	30	4 330	980
Mollusca	420	270	490	490	130	120	150	130	880	560
Crustacea	30	20	40	40	20	10	160	30	120	10
Echinodermata	140	30	40	40	60	130	110	10	700	190
Others	190	160	210	210	80	160	190	90	5 110	5 370
Total	1 660	1 480	2 320	2 070	830	990	1 430	970	24 690	11 600
Wet weight (g m^{-2})										
Polychaeta	28.102	47.441	13.967	22.761	16.550	10.941	20.303	16.616	36.516	17.127
Oligochaeta	–	–	0.025	–	–	–	0.011	0.002	0.867	0.162
Mollusca	39.574	36.115	23.320	17.771	13.850	5.979	1.185	6.202	48.841	57.925
Crustacea	0.233	0.156	0.149	0.043	9.143	0.002	10.290	0.149	0.536	0.001
Echinodermata	0.296	0.006	0.010	0.008	8.866	1.686	0.012	0.003	5.987	0.292
Others	0.395	0.421	0.098	7.822	0.070	0.451	0.940	0.173	33.450	14. 469
Total	68.800	84.139	37.569	48.405	48.479	19.059	32.741	23.145	126.197	89.976

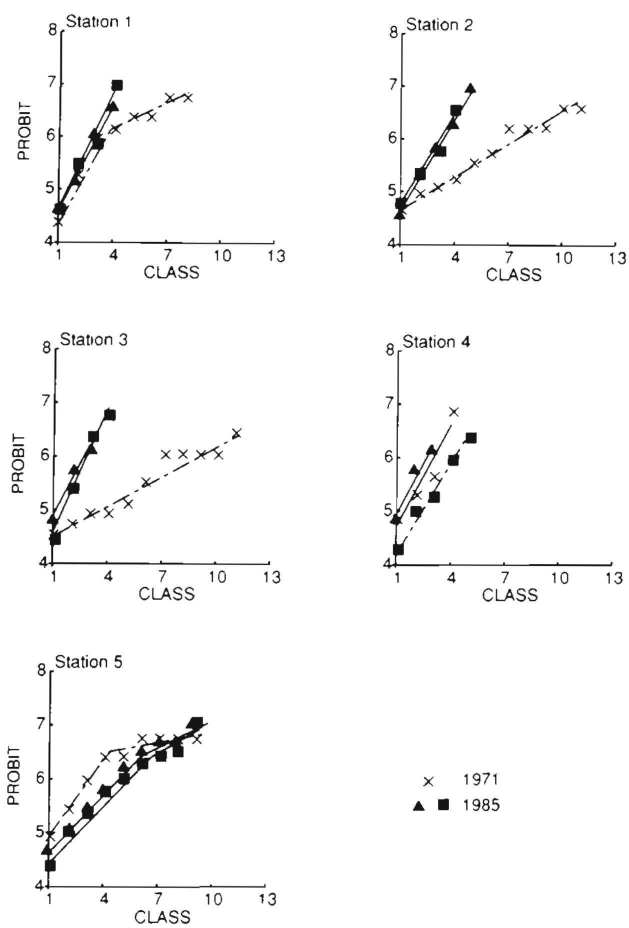

Fig. 1 Log-normal (Gray & Mirza 1979) plots of fauna from Stns 1 to 5 for 1985, also showing 1971 data from Topping & McIntyre (1972)

5 species (Table 3) shows that the opportunist polychaetes Capitellidae and *Peloscolex (Tubificoides)* sp. accounted for a very large proportion of the total abundance in 1971, especially at Stns 2 and 3 (93 and 94 % respectively). Only 2 species of mollusc were represented in the top 5 ranking (*Thyasira flexuosa* and *Nucula turgida*) and, with the exception of the Nemertea, the remainder were annelids. No crustaceans were present in the top 5 grouping and only a few specimens were taken overall. Echinoderms were represented only by an occasional juvenile ophiuroid. In 1985, the fauna was much more diverse, and less dominated by opportunist species.

The log-normal distributions (Fig. 1) suggest that, with the exception of Stn 4, the 1971 stations exhibited either a dog-leg condition or a shallow gradient. They also had a larger number of geometric classes present than the more 'normal' community at Stn 4. The absence of representatives of classes V and VI, or VII to X, accounted for the dog-leg and shallow gradient conditions respectively.

DISCUSSION

In attempting to make comparisons between a limited number of stations sampled on only 2 occasions 14 yr apart, the authors recognise that vigorous statistical analysis is not possible, and that reliance has been placed upon descriptive techniques and faunal indices. In support of this approach, it may be noted that at Stn 4 (least affected by the disposal operation) there was

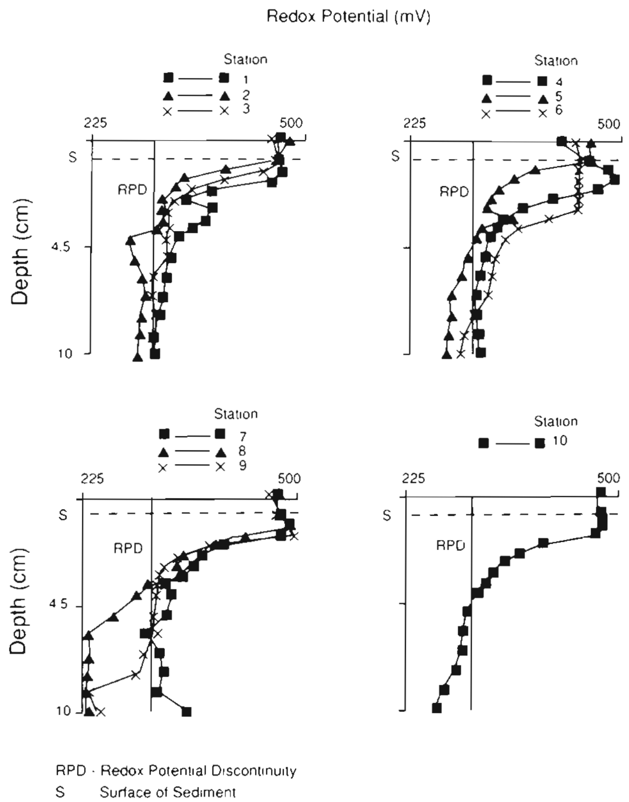

Fig. 2. Profiles of redox potential in the sediment from Stns 1 to 10 at the pre-1974 dump site

good agreement between the 1971 and 1985 faunal indices and log-normal distribution patterns. Movement to the new disposal site had no noticeable impact on the fauna at this station, and redox values remained positive throughout the upper 10 cm of sediment. This suggests that differences at other stations may reflect real changes in the benthic communities. Pearson et al. (1986) studied the composition of macrobenthic communities in the Clyde Sea area and concluded that the area was generally enriched due to high nutrient inputs, particularly to the Arran/Ayrshire basin. Localised waste disposal contributed to the high carbon input, and species indicative of organically enriched sediments would therefore be present naturally (see Table 1).

In 1971, 4 stations (1, 2, 3 and 5) had very modified communities, as indicated by the diversity and evenness indices. By 1985, the faunal indices at Stns 1 to 4 had returned to values similar to those exhibited by communities from similar sediment types in the Clyde but remote from the dumping site. Although some of the species found, e.g. *Capitella capitata* and *Chaetozone setosa*, are considered as indicative of organic enrichment, they were present in relatively low numbers.

The diversity and evenness indices at Stn 5 (Table 4) showed a marked improvement between 1971 and 1985, but the community continued to show the lowest diversity and evenness, despite the presence of a high total number of species. Twenty-one species occurred exclusively at this station in 1985 and the fauna contained representatives of all the characteristic groupings suggested by Pearson et al. (1986) as being present in a gradation over the sludge dumping grounds (see Table 1). Although insufficient stations were sampled in 1985 to be able to establish detailed gradients of effect in the manner suggested by Pearson & Rosenberg (1978), Stn 5 may represent a transition zone between the now slightly enriched area at the pre-1974 disposal area, and the heavily enriched present disposal site.

The dog-leg condition in log-normal plots has been associated (Gray & Mirza 1979) with communities in transition through stress. Lines with a shallow slope, covering a large number of geometric groups, are considered to represent stressed communities which are in equilibrium, and steeply sloping lines, with few geometric classes, represent unstressed equilibrium communities. The log-normal distributions of the 1971 data suggest that the communities at Stns 2 and 3 were

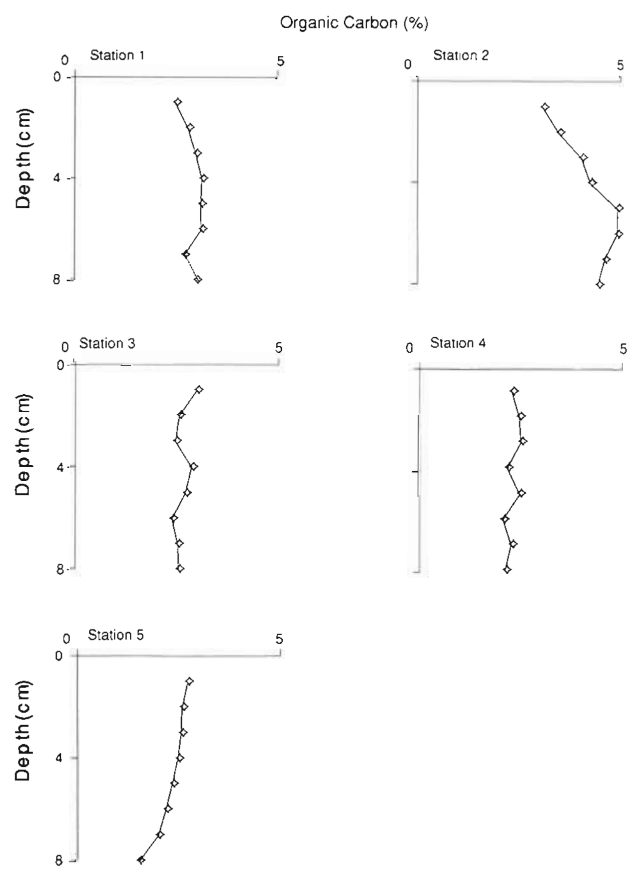

Fig. 3. Concentrations of organic carbon (%) in the sediment from Stns 1 to 5 at the pre-1974 dump site

Table 3. Top 5 species dominance lists for Garroch Head old dump site, Stns 1 to 5, 1971 (Topping & McIntyre 1972) and 1985. Cum. % cumulative percentage of total abundance at each site

1971	Ind. m^{-2}	Cum. %	1985	Ind. m^{-2}	Cum. %
Station 1					
Capitellidae	3 170	67.88	Nemertea	160	10.03
Eunicidae (juv.)	680	82.44	*Chaetozone setosa*	130	18.18
Nemertea	240	87.58	*Abra alba*	115	25.39
*Paraonis gracilis (Levensenia)**	80	89.39	*Spiophanes kroyeri*	105	31.97
Nucula turgida	70	90.78	*Prionospio malmgreni*	85	37.30
Station 2					
Peloscolex sp.	32 550	77.37	*Spiophanes kroyeri*	270	12.24
Capitellidae	6 520	92.87	*Thyasira flexuosa*	235	22.90
Audouinia sp. *(Cirriformia)**	970	95.18	*Chaetozone setosa*	140	29.25
Cirratulidae	820	97.12	Nemertea	130	35.15
Cirratulus sp.	570	98.48	*Nuculoma tenuis* *Nucula sulcata* *Mediomastus* sp.	115	40.36
Station 3					
Peloscolex sp.	31 670	60.32	*Spiophanes kroyeri*	115	12.64
Capitellidae	17 740	94.11	Nemertea	95	23.08
Eunicidae (juv.)	1 100	96.21	*Minuspio cirrifera*	80	31.87
Cirratulidae	820	97.77	Ophiuroidea	80	40.66
Cirratulus sp.	540	98.90	*Nephtys hystricis*	60	47.25
Station 4					
Chaetozone setosa	590	17.93	*Tharyx marioni**	250	12.50
Capitellidae	350	28.93	*Minuspio cirrifera*	130	23.33
Diplocirrus glaucus	350	39.57	*Spiophanes kroyeri*	105	32.08
*Paraonis gracilis (Levensenia)**	240	46.51	Nemertea	90	39.58
Eunicidae (juv.) Nemertea	200	52.58	*Levensenia gracilis*	60	45.42
Station 5					
Capitellidae	8 370	89.14	*Mediomastus* sp.	5185	28.58
Scolelepis fuliginosa	370	93.08	Nematoda	5185	57.06
Nemertea	130	94.46	Oligochaeta (indet.)	2335	69.90
Chaetozone setosa	100	95.53	*Capitella capitata*	1445	77.85
Lumbrinereis sp. *Paraonis gracilis (Levensenia)** *Thyasira flexousa*	50	96.06	*Ophryotrocha hartmanni*	610	81.21

* Synonym (after Howson 1987)

severely stressed but in equilibrium and that Stns 1 and 4 were in a transitional state. The 1985 plots, however, suggest that the communities at Stns 1 to 4 have returned to equilibrium unstressed conditions, but that Stn 5 continues to exhibit transitional characteristics.

The increase in diversity in the fauna since dumping of sewage sludge ceased has been accompanied by decreases in the organic carbon content in surface (0 to 1 cm) sediments, consistent with a reduction of the input of sludge, increased importance of natural sedimentation and possibly continuing mineralisation of sewage solids. The presence of elevated organic carbon and trace metal concentrations at depth in Stn 2 (Rodger et al. 1991) suggests the persistence of historical contamination by sewage sludge in these subsurface sediments.

There has been an obvious improvement in the status of the communities at the 4 stations strongly impacted in 1971 as assessed by the various community indices, consistent with the changes in sediment organic carbon and redox potentials. The individual sample abundance and biomass has returned to levels typical of the slightly enriched environment of the Clyde. Only Stn 5 showed any effects of sludge input, and this may be

Table 4. Shannon-Wiener (SW) and Heip indices of diversity and evenness for Garroch Head old dump site, Stns 1 to 5, 1971 (Topping & McIntyre 1972) and 1985

	1971	1985		
		Sample 1	Sample 2	Total
Station 1				
No. species	23	42	34	51
SW index	1.300	3.315	3.127	3.412
Heip index	0.121	0.647	0.661	0.586
Station 2				
No. species	17	51	40	64
SW index	0.802	3.408	3.087	3.402
Heip index	0.077	0.584	0.536	0.461
Station 3				
No. species	13	24	31	44
SW index	0.932	2.793	3.037	3.242
Heip index	0.128	0.666	0.661	0.572
Station 4				
No. species	35	32	32	46
SW index	2.941	2.995	3.062	3.215
Heip	0.527	0.613	0.657	0.531
Station 5				
No. species	24	52	47	63
SW index	0.601	2.182	1.971	2.201
Heip index	0.036	0.154	0.134	0.130

Table 5. Summary of abundance, biomass, diversity and evenness indices of benthic macrofauna at Garroch Head, old dump site, Stns 1 to 5. Data from Topping & McIntyre (1972)

	Station				
	1	2	3	4	5
Abundance (ind. m^{-2})					
Polychaeta	4 220	9 550	20 820	2 610	9 120
Oligochaeta	20	32 550	31 670	120	–
Mollusca	180	–	–	270	110
Crustacea	–	–	–	20	60
Echinodermata	–	10	–	10	–
Others	250	10	10	240	140
Total	4 670	42 070	52 500	3 270	9 430
Wet weight biomass (g m^{-2})					
Polychaeta	15.419	40.091	102.157	82.583	37.922
Oligochaeta	0.010	56.683	56.000	0.073	–
Mollusca	12.030	–	–	12.365	12.434
Crustacea	–	–	–	0.060	0.110
Echinodermata	–	0.010	–	0.010	–
Others	2.679	0.010	4.550	2.679	1.445
Total	30.138	96.794	162.707	97.770	51.911

attributable to the marginal effects of the current disposal operation.

In part the improvement in the macrobenthic communities parameters may be an artefact of improvements in the faunal analysis but the similarity between the 1985 and 1971 data for Stn 4 shows that this factor is of minor importance and alone cannot account for the gross changes observed in the community statistics. Warwick (1988) has shown that similar trends can be recognised in faunal data analysed at various taxonomic levels, suggesting that the apparent recovery of the fauna at the old Garroch Head disposal site may be considered as a reliable reflection of the resilience of the marine environment.

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