## 6.3 Conclusions

Organic matter discharged in dredger outwash has been reported by Newell *et al*. (1999) whilst direct measurements of plume morphology from dredgers operating during normal loading of screened cargoes on the Owers Bank close to the east of the North Nab survey area have been reported by Hitchcock and Drucker (1996; see also Hitchcock *et al*., 1998). These studies suggest that the main zone of sedimentation of organic matter from the dispersing plume is likely to be up to 3 km downstream along the axis of dispersion on the tidal stream, and closer to the site of discharge on an axis perpendicular to the tidal stream. An elongated 'halo' of deposition of fine material including fragmented organic matter, with a long axis of approximately 3 km downstream on each side of the dredge site would be anticipated from dispersion profiles recorded on the Owers Bank and from measurements of organic matter in dredger outwash in the southern North Sea.

The results reported here suggest that population density, species diversity, biomass and body size of the macrofauna are enhanced in a broad zone that corresponds with the anticipated elongated 'halo' of deposition of material from the dispersing outwash plume originating in the intensively-dredged site. The zone of enhanced benthic population density, species diversity and biomass is evidently truncated in the eastern part of the survey area by the presence of sand but in all other respects conforms with what might be anticipated from a regular release of particulate organic matter from a point source within the survey area. Values for the number of species (*S*), the number of individuals (*N*) and the biomass (*B*) expressed as grams AFDW per 0.2 $m^2$ at each of the stations showing enhancement of benthos surrounding the North Nab dredge site are summarised in Text Table 6.3.

It is clearly not possible to ascribe a cause-and-effect relationship between the zone of enhanced benthos surrounding the North Nab dredge site and dredging activities within the intensively dredged part of Production Licence Area 122/3. The results suggest, however, that repeated and intensive dredging at the North Nab anchor-dredge site may provide a sufficiently rich and predictable source of organic matter from dredger outwash to have an impact on benthic community structure up to 3 km downstream of the dredge site, and closer to the dredge site across the axis of dispersion on the tidal current.

| Station # | No. of Species (*S*) | Population Density (*N*) per 0.2 m² | Biomass (B) g AFDW per 0.2 m² |
|---|---|---|---|
| 18 | 33 | 623 | 5.5984 |
| 34 | 47 | 396 | 11.7270 |
| 37 | 26 | 918 | 21.8398 |
| 38 | 30 | 1223 | 9.3850 |
| 39 | 22 | 267 | 2.1763 |
| 40 | 29 | 274 | 1.9507 |
| 41 | 26 | 268 | 4.0510 |
| 53 | 24 | 192 | 3.7748 |
| 54 | 35 | 318 | 3.8566 |
| 55 | 8 | 88 | 5.0308 |
| 57 | 44 | 163 | 5.0756 |
| 58 | 39 | 142 | 4.4844 |
| 71 | 37 | 518 | 9.5504 |
| 85 | 42 | 189 | 8.3026 |
| 95 | 39 | 245 | 3.4610 |
| 108 | 35 | 289 | 26.1456 |
| 135 | 36 | 1337 | 13.2447 |
| 142 | 68 | 492 | 5.3613 |
| 143 | 64 | 848 | 10.6218 |
| 144 | 71 | 1423 | 27.8532 |
| 145 | 48 | 546 | 9.0035 |
| 146 | 52 | 599 | 7.6634 |
| 150 | 60 | 679 | 3.1514 |
| **Mean** | **39.8** | **523.3** | **8.8395** |
| **D** | **15.6** | **389.2** | **7.2621** |
| **N** | **23** | **23** | **23** |

**Text Table 6.3** Table summarising the species variety (*S*), the population density (*N*) and biomass (*B*) g AFDW per 0.2 m² Hamon Grab sample at each of the stations showing enhancement of benthos surrounding the North Nab 122/3 dredge site.

The only data available for organic releases in the outwash of an operating dredger are for a screened cargo in a newly exploited deposit in the southern North Sea (Newell *et al.*, 1999). Such values are likely to be higher than those for non-screened ('all-in') cargoes taken from an area where the gravels have been heavily exploited and which therefore contain relatively poor benthic invertebrate communities. The following section gives some values for the particulate and organic matter actually released during anchor dredging at the North Nab site, together with estimates of the likely source of the organic matter and its significance for benthic communities.

### 6.4 Significance of Dredger Outwash: A Mass Balance Approach

In an earlier mass balance study of the inorganic particulate load and organic content of discharges from a dredger loading a screened cargo of 5,630 tonnes in the southern North Sea off Southwold, Suffolk it was shown that as much as 8713 tonnes of material were rejected via the screening chute and 360 tonnes through outwash from hopper spillways. Organic matter measured in the outwash and assumed to apply to the entire water discharged from both screening chute and hopper outwash was as much as 41.5 tonnes comprising 0.20 tonnes of lipids.

The corresponding concentrations in the outwash of the dredger were 12.6 g per litre of sediment, 1.45 g AFDW per litre of organic matter and 0.0007 g per litre of lipids. These values were the first direct measurements of the concentration of organic matter in the outwash from a marine aggregates dredger, and compare with a detrital load in rich kelp-bed ecosystems of 0.78-1.04 mg AFDW per litre (Seiderer and Newell, 1985; Newell *et al*., 1999).

That is, the organic matter in the outwash from a dredger operating in the southern North Sea in newly-exploited deposits to the east of Southwold, Suffolk was about 1,500 times the organic content of some of the richest detrital ecosystems in the world.

Estimates based on the biomass of benthic invertebrates likely to be ‘processed’ by the dredger during normal loading operations suggested that relatively large quantities of organic matter could be derived from fragmentation of the benthos. During loading of a 4,500 tonne cargo recorded by Hitchcock and Drucker (1996), a maximum of some 35.3 tonnes AFDW of organic matter based on benthic invertebrates could be discharged in the 33,866 tonnes of water from the dredger. Since the volume of the outwash is known, the concentration of the organic matter derived from fragmented benthic invertebrates can be calculated. This indicates that a yield of 1,012.6 mg AFDW per litre could be derived from benthic invertebrates fragmented during processing of the 14,703 tonnes of sediment required to obtain a screened cargo of 5,630 tonnes.

The work reported by Newell *et al*. (1999) suggested that for a newly exploited area in the southern North Sea, organic enrichment may be of sufficient concentration to account for the "far field" visibility of the dispersing plume downstream from aggregate dredgers. It may also account for the increase in species diversity and population density, which has been reported for the benthos adjacent to dredged areas (see Poiner and Kennedy, 1984). There have, however, been no measurements of the composition of the outwash from dredgers operating in other dredge areas, especially in those where previous dredging activities have already had an impact on the benthos.

In the case of the North Nab Production Licence Area 122/3, the benthic biomass is already relatively low in the dredged site, and this is likely to reduce the organic content of material derived from fragmented invertebrates in the outwash. Because the aggregate is loaded as an 'all-in' (unscreened) cargo, the amount of material processed by the dredger is lower than that for a screened cargo where as much as 1.5-1.6 x the cargo is rejected. Both inorganic and organic losses from unscreened cargoes are therefore likely to be lower than from screened ones.

It is of interest to quantify the inorganic particulate losses and the organic load discharged from the dredger actually operating at the North Nab site, and to assess the extent to which the known benthic resources at the dredge site could account for the organic emissions in the outwash. The following estimates were made based on analysis of data for outwash from the dredger *City of Chichester* operating on the North Nab anchor-dredge site on 1st February 2000. An unscreened cargo of 2,141 tonnes was loaded which, because of poor weather, was less than the normal cargo of 2,400 tonnes. The total volume of water discharged during loading was 1,178 tonnes, and is visible as a plume downstream of this and other dredgers during loading (Plate 6.4).

**Plate 6.4**. Photograph showing the plume of dispersing outwash being carried westwards on the ebbing tide during loading of a cargo at station 126 of the North Nab Study site by the City of Cardiff on 13.03.99.

The positions of the sites at which dredging took place, and where simultaneous samples of outwash water were taken are summarised in Text Table 6.4a.

| Time | Latitude ° N | Longitude ° W | Easting (m) | Northing (m) |
|---|---|---|---|---|
| 11:15:04 | 50 39.4871 | 00 58.9400 | 471925.1 | 84829.9 |
| 11:30:02 | 50 39.4839 | 00 58.9390 | 471926.4 | 84824.0 |
| 11:45:02 | 50 39.4871 | 00 58.9340 | 471935.3 | 84824.2 |
| 12:00:00 | 50 39.4880 | 00 58.9280 | 471939.2 | 84831.8 |
| 12:15:06 | 50 39.4900 | 00 58.9280 | 471939.2 | 84835.5 |
| 12:30:06 | 50 39.4910 | 00 58.9130 | 471956.8 | 84838.6 |
| 12:44:08 | 50 39.4900 | 00 58.8720 | 472005.2 | 84836.4 |
| 13:17:08 | 50 39.3469 | 00 59.1380 | 471695.6 | 84566.9 |
| 13:30:04 | 50 39.3459 | 00 59.1230 | 471713.2 | 84565.3 |
| 13:45:02 | 50 39.3379 | 00 59.1060 | 471733.4 | 84550.8 |
| 14:00:00 | 50 39.3401 | 00 59.1090 | 471729.8 | 84554.8 |
| 14:15:00 | 50 39.3369 | 00 59.1020 | 471738.1 | 84549.0 |
| 14:30:06 | 50 39.3401 | 00 59.1030 | 471736.9 | 84554.9 |
| 14:45:04 | 50 39.3379 | 00 59.1000 | 471740.5 | 84550.9 |
| 15:00:02 | 50 39.3391 | 00 59.0920 | 471749.8 | 84553.2 |
| 15:15:02 | 50 39.3411 | 00 59.0820 | 471761.6 | 84557.1 |
| 15:30:00 | 50 39.3420 | 00 59.0680 | 471778.0 | 84559.0 |

**Text Table 6.4a.**Table summarising the positions of the dredger City of Chichester during loading of a cargo on 01.02.00. when a series of samples of outwash were taken for subsequent analysis of particulate load and organic composition. Positions in latitude and longitude and in OSGB 36 were taken from the ship's log. See also Figure 6.4a.

Because of poor weather conditions, the dredger drifted eastwards from a starting position close to Station 124 at 11h15. At 12h44 dredging was stopped and the vessel relocated at 13h17 near Station 126 where loading continued until 15h30. A map showing the positions of the sampling stations in the anchor-dredge area is shown in Figure 6.4a. The boundaries of the anchor-dredge area are shown, as well as the tracks of the dredger City of Chichester during the loading of a cargo on 01.02.00.

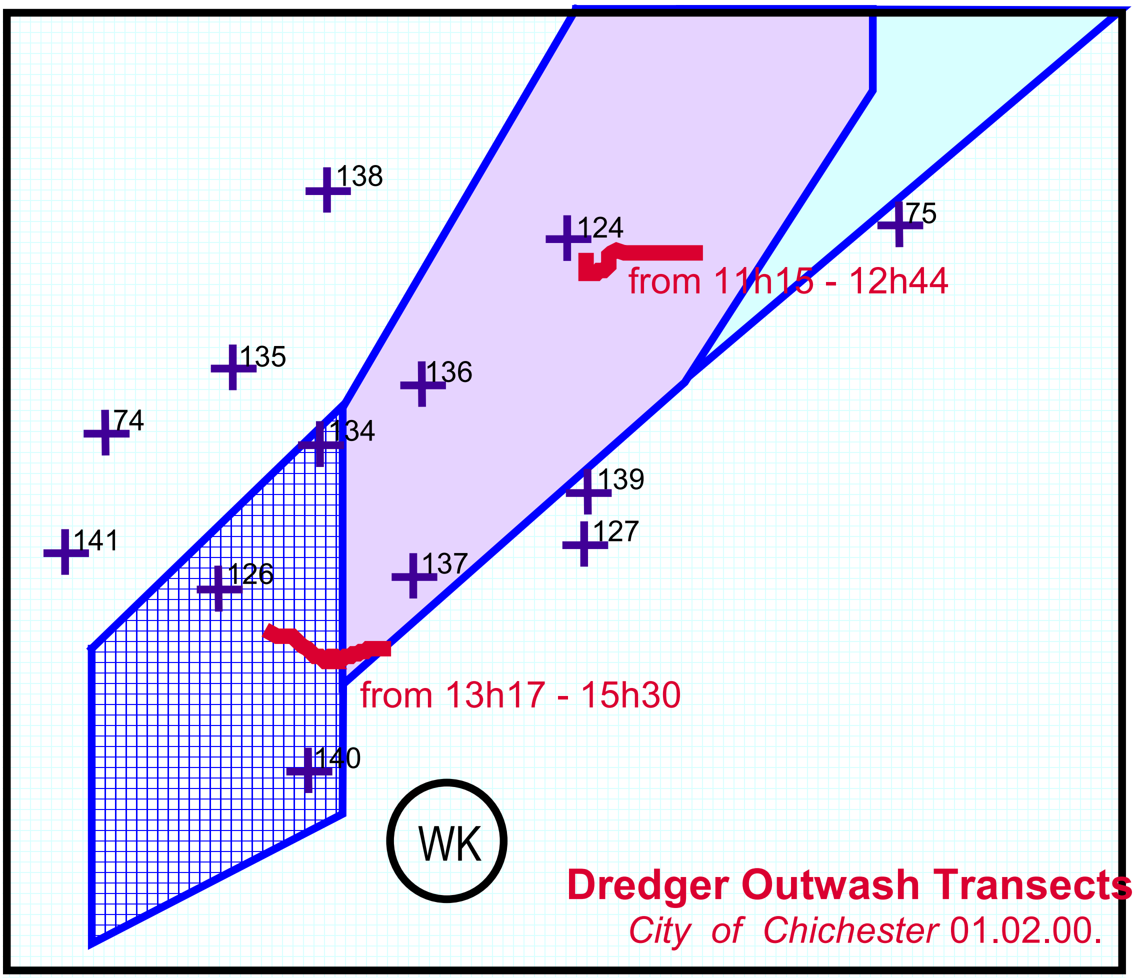


**Figure 6.4a**. Map of part of the dredge site showing the tracks of the dredger City of Chichester during loading of a cargo on 01.02.00 when samples of outwash were taken for analysis of particulate load and organic material discharged during loading operations. See also Text Table 6.4.

A total of 50 water samples were taken from the hopper outwash at intervals during the loading period of 3 hours 13 min. From the results obtained, the background values for suspended solids and organic matter were subtracted to give the results shown in Text Table 6.4b. The average values for suspended solids and organic matter (mg AFDW per litre) were calculated from the data shown in Text Table 6.4b.

| Sample | Time after start of dredging (minutes) | Total suspended solids (- controls) mg/l | Ashed suspended solids (- controls) mg/l | Organics AFDW mg/l |
|---|---|---|---|---|
| 1 | 1 | 248 | 208 | 40 |
| 2 | 3 | 419 | 249 | 170 |
| 3 | 6 | 521 | 417 | 104 |
| 4 | 9 | 177 | 134 | 43 |
| 5 | 12 | 479 | 385 | 94 |
| 6 | 15 | 533 | 413 | 120 |
| 7 | 18 | 663 | 529 | 134 |
| 8 | 21 | 457 | 378 | 79 |
| 9 | 24 | 514 | 418 | 96 |
| 10 | 27 | 553 | 451 | 102 |
| 11 | 30 | 779 | 635 | 144 |
| 12 | 33 | 1589 | 1363 | 226 |
| 13 | 36 | 1299 | 1103 | 196 |
| 14 | 39 | 711 | 593 | 118 |
| 15 | 42 | 424 | 363 | 61 |
| 16 | 45 | 683 | 578 | 105 |
| 17 | 48 | 655 | 541 | 114 |
| 18 | 51 | 641 | 541 | 100 |
| 19 | 54 | 845 | 719 | 126 |
| 20 | 57 | 452 | 389 | 63 |
| 21 | 60 | 853 | 693 | 160 |
| 22 | 65 | 905 | 747 | 158 |
| 23 | 68 | 1059 | 895 | 164 |
| 24 | 109 | 1259 | 1073 | 186 |
| 25 | 113 | 2239 | 1893 | 346 |
| 26 | 117 | 1129 | 989 | 140 |
| 27 | 121 | 2439 | 2103 | 336 |
| 28 | 125 | 1629 | 1393 | 236 |
| 29 | 129 | 2389 | 2033 | 356 |
| 30 | 133 | 1789 | 1543 | 246 |
| 31 | 137 | 2479 | 2163 | 316 |
| 32 | 141 | 1569 | 1313 | 256 |
| 33 | 145 | 2029 | 1733 | 296 |
| 34 | 149 | 1649 | 1413 | 236 |
| 35 | 153 | 1629 | 1393 | 236 |
| 36 | 159 | 1819 | 1543 | 276 |
| 37 | 163 | 3399 | 2963 | 436 |
| 38 | 167 | 2259 | 1923 | 336 |
| 39 | 171 | 2519 | 2163 | 356 |
| 40 | 175 | 1439 | 1223 | 216 |
| 41 | 182 | 764 | 652 | 112 |
| 42 | 188 | 1209 | 1046 | 163 |
| 43 | 194 | 792 | 678 | 114 |
| 44 | 200 | 2629 | 2245 | 384 |
| 45 | 206 | 2179 | 1843 | 336 |
| 46 | 212 | 3339 | 2853 | 486 |
| 47 | 219 | 3489 | 2983 | 506 |
| 48 | 226 | 5371 | 4653 | 718 |
| 49 | 231 | 426 | 359 | 67 |

| | | | | |
|---|---|---|---|---|
| 50 | 233 | 642 | 535 | 107 |
| **Mean** | **-** | **1399.24** | **1188.29** | **210.32** |
| **SD** | **-** | **1047.17** | **910.4** | **138.55** |

**Text Table 6.4b**.Showing the total suspended solids minus the mean background value (mg/l), the ashed suspended solids minus the mean background value (mg/l) and the organic component (AFDW mg/l), recorded in a series of 50 water samples taken from "outwash" water discharged from the marine aggregate dredger City of Chichester anchored in North Nab Licence Area 122/3, South East of the Isle of Wight, on 01.02.00. Background levels based on two samples of seawater taken before dredging started and two samples taken after dredging had ceased. Total background suspended solids = 31.25 mg per litre, N = 4; organic matter (AFDW) = 24 mg per litre, N = 4.

| **Inorganic Matter:** | |
|---|---|
| Volume of Water Discharged | = 1,178 tonnes. |
| Concentration of Inorganic Suspended Solids | = 1,399.24 mg per litre (sd 1,047.17) |
| | = 1,399.24 grams per tonne of discharge water |
| Therefore 1,178 tonnes of Discharge Water | = 1,178 x 1,399.24 grams |
| **Inorganic Matter Discharged:** | **= 1,648.3 kg per cargo load of 2,141 tonnes.** |

| **Organic Matter:** | |
|---|---|
| Volume of Water Discharged | = 1,178 tonnes |
| Concentration of Organic Matter | = 210.32 mg AFDW per litre (s.d. 138.55) |
| | = 210.32 grams per tonne of discharge water |
| Therefore 1,178 tonnes of Discharge Water | = 1,178 x 210.32 grams AFDW Organics |
| **Organic Matter Discharged:** | **= 247.8 kg per cargo load of 2,141 tonnes.** |

This can be compared with approximately 9,000 tonnes total sediment released from a screened cargo of 5,630 tonnes and an organic discharge of 41.5 tonnes from a cargo loaded off Southwold in the southern North Sea (Newell *et al*., 1999). A comparison of the mass balance for discharges from a dredger loading a screened cargo of 5,630 tonnes off Southwold, Suffolk in April 1998 and that for the City of Chichester loading an unscreened cargo of 2,141 tonnes in the North Nab Production Licence Area 122/3 is shown in Text Table 6.4c.

| | Tonnes Discharged for a screened cargo of 5,630 tonnes | Tonnes discharged for an unscreened cargo of 2,141 tonnes |
|---|---|---|
| Water | 28,552 | 1,178 |
| Sediment in hopper outwash | 360 | 1.648 |
| Sediment rejected by screening | 8,713 | - |
| TOTAL SEDIMENT REJECTED | 9,073 | 1.648 |
| Organic matter (AFDW) | 41.5 | 0.248 |

**Text Table 6.4c**. Mass discharges of material from a trailer-dredger loading a screened cargo of 5,630 tonnes of gravel off Southwold, Suffolk in April 1998 (based on Newell *et al*., 1999). Also shown are data for mass discharges from the City of Chichester loading an unscreened cargo of 2,141 tonnes in February 2000 at North Nab Production Licence Area 122/3 to the east of the Isle of Wight, UK.

| **Source of Organic Matter in the Outwash** | |
|---|---|
| Total Organic Matter Discharged | = 247.8 kg AFDW per cargo of 2,141 tonnes |
| | = 115.74 grams AFDW per tonne |
| **Organic Matter in Outwash:** | **= 115.74 mg AFDW per kg sediment** |

| **Source of Organic Matter Available from Benthos** | |
|---|---|
| AFDW Benthos in Anchor-Dredge Area | = 2.0 g AFDW per 0.2 m² (see Figure 26 ) |
| | = 2.0 g AFDW per 19.1 kg sediment (App. 1) |
| Benthos in 19.1 kg sediment | = 2000 mg AFDW |
| Benthic contribution to 1 kg sediment | = 2000 / 19.1 mg AFDW |
| **Organic Matter from Benthos** | **= 104.71 mg AFDW per kg sediment** |

That is, the amount of organic matter actually measured from spillways of the City of Chichester operating at the North Nab anchor-dredge site on 1st February 2000 amounted to an equivalent of 115.74 mg AFDW per kg sediment loaded. Of this, the measured benthic resources in the dredge area itself could supply at least 104.7 mg AFDW organic matter per kg of sediment.

Clearly there is a correspondence between the organic composition of the outwash, and the concentration of material that would be anticipated from fragmented invertebrates discharged from the dredger at the actual site of dredging. The total annual cargo loaded is approximately 150,000 tonnes. The total organic matter released into the water column by dredging from this very restricted area of seabed is therefore 0.11574 kg x 150,000 = 17.36 tonnes AFDW organic matter per year. It is not known whether this value is sufficient to sustain and enhance the filter-feeding benthic invertebrate populations that occur along the axis of dispersion of outwash from the dredge site.

## 6.5 Production Estimates for the Benthic Community

Production values for benthic communities are often estimated from the biomass using Production/Biomass (P/B) ratios derived from a variety of sources including whole communities and individual species. The mean value for the biomass of benthic invertebrates in the North Nab survey area was 2.11 g AFDW per 0.2 m² Hamon grab sample (Text Table 6.1.2a) and the mean value for those stations surrounding the dredged area which showed an enhanced benthos was 8.8 g AFDW per 0.2m (Text Table 6.2.5). Mann (1982) gives the ratio of 1 gram of carbon = 2.6 grams AFDW organic matter. The average biomass of benthos in the North Nab survey area as a whole is therefore 0.8115 g C per 0.2 m² and that in the zone of enhancement or "halo" surrounding the dredged area is 3.4 g C per 0.2 m². This is equivalent to an average biomass of 4.06 g C per m² and a biomass in the zone of enhancement of 17 g C per m². Some values for coastal communities summarised from the literature are shown in Text Table 6.5a.

| Location | Depth (m) | B gC/m² | P/B | P gC/m²/yr | Reference |
|---|---|---|---|---|---|
| Estuary, Netherlands | 0 | 10 | 1.6 | 16.5 | Wolff and de Wolff (1977) |
| Estuary, Cornwall | 0 | 5.3 | 1.0 | 5.3 | Warwick and Price (1975) |
| Severn Estuary | 17 | 17.0 | 0.6 | 10.0 | Warwick *et al*. (1979) |
| Long Island Sound | 18 | 4.8 | 2.5 | 12.0 | Sanders (1958) |
| Baltic | 46 | 1.7 | 1.6 | 2.7 | Cederwall (1977) |
| North Sea | 80 | 1.7 | 0.4 | 0.7 | Buchanan and Warwick (1974) |
| All Areas Mean | - | 6.75 | 1.28 | 7.87 | |
| SD | - | 5.87 | 0.78 | 6.01 | |
| **North Nab Mean** | **10-20** | **4.06** | **(1.28)** | **5.2** | **This study** |
| **Max.** | | **17.0** | | **21.8** | **This study** |

**Text Table 6.5a** Table showing values for the biomass of benthic macrofauna from various habitats. Data have been converted to grams of carbon per m² using the ratio of AFDW X 0.4 (based on Mann, 1982). Note that the average biomass for the study area at North Nab is generally similar to that recorded for other habitats, but that the biomass adjacent to the dredged area is comparable with that of estuaries. Assuming a P/B ratio of 1.28 for the North Nab study site, the production (P) value is 5.2 gC/m²/yr for the survey area as a whole, but is as high as 21.8 gC/m²/yr for the zone of enhanced benthos adjacent to the dredged site.

Several features of interest emerge from comparison of the data for the North Nab survey area with those for other coastal habitats. The biomass values for typical estuarine communities are 10-17 grams carbon per m² whilst those for the Baltic and North Sea are reported to be only 1.7 grams carbon per m². Clearly the average biomass of 4.06 grams carbon per m² for the North Nab survey area is relatively high compared with shelf seas whilst that in the ‘halo’ of enhanced benthos approaches that of the Severn estuary (Warwick *et al*., 1979). Benthic biomass in estuaries is enhanced by fragmented organic debris from coastal wetlands. We surmise that the release of 17.36 tonnes of organic matter per year from the North Nab dredge site may be sufficient to account for benthic production values that approach those of estuarine communities.

Whilst there is no data on annual production values for the benthos of the North Nab survey area, there is some information on the American slipper limpet (*Crepidula fornicata*), which occurs in abundance outside the boundaries of the dredged area. Production / Biomass ratios vary a good deal, but an average value of 1.28 is obtained for the sites summarised in Text Table 6.5a. Using this value, average annual production by the benthos in the North Nab survey area is likely to be approximately 5.2 grams carbon per m² with values as high as 21.8 grams carbon per m² in peripheral stations of enhanced biomass extending down the tidal stream from the dredged site.

## 6.6 Biomass and Production Estimates for a Key Consumer

### 6.6.1 Population Structure of *Crepidula fornicata*.

The mollusc community adjacent to the dredged area is dominated by the filter-feeding American Slipper Limpet (*Crepidula fornicata*). This gastropod feeds on particulate matter suspended in the water column and was introduced to Europe with the American oyster, *Crassostrea virginica*. The numbers of *Crepidula fornicata* recorded per 0.2 m² Hamon grab sample in the deposits adjacent to the North Nab dredge site are summarised in Figure 6.6.1a (see also Appendix Table 8).

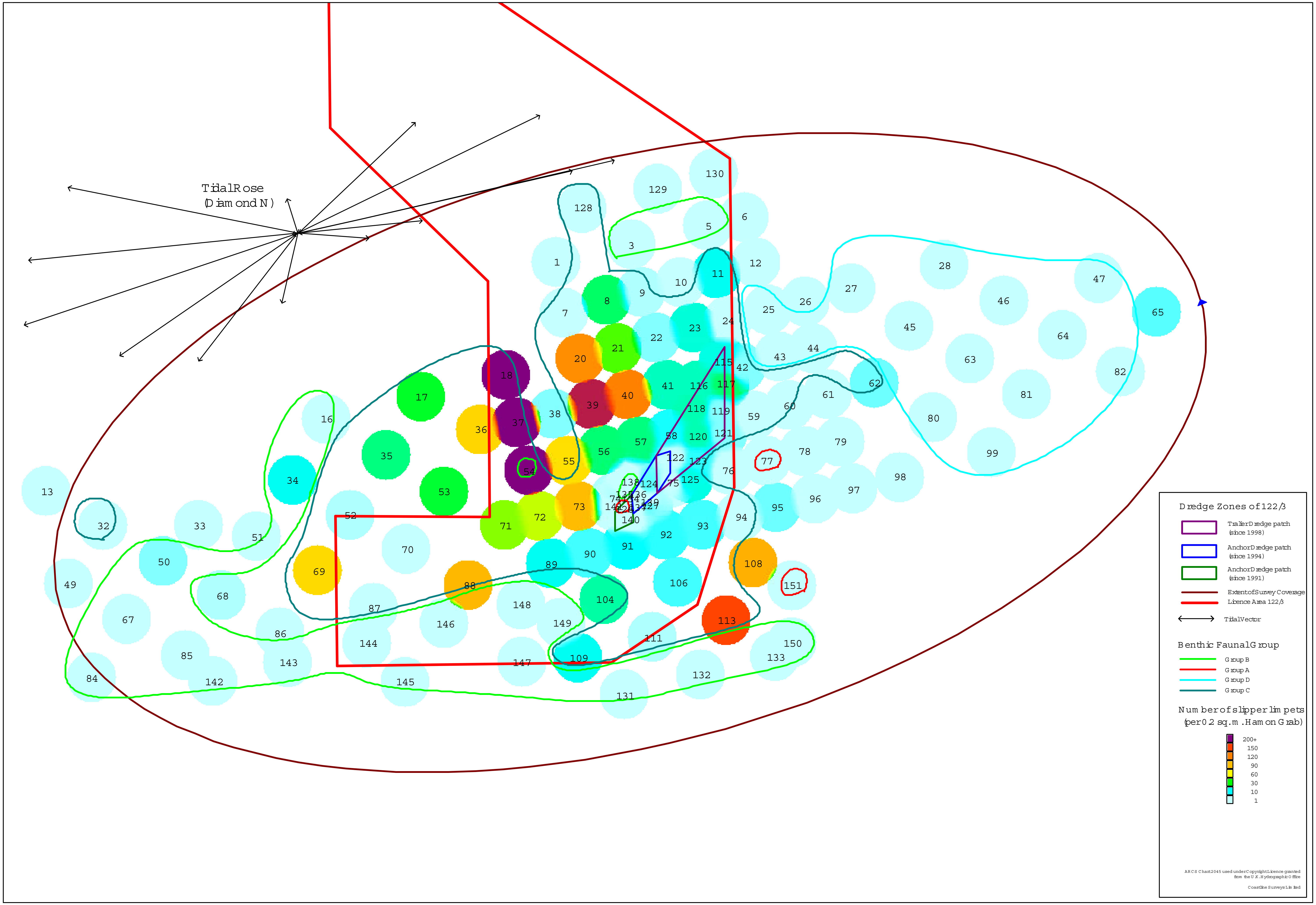


Figure 6.6.1a. Map of the North Nab survey area showing a grid thematic map
for the number of slipper limpets per 0.2 sq.m. Hamon Grab.

This shows that population densities as high as 250 individuals per 0.2 $m^2$ occur close to the west of the dredge site and that similar relatively high densities occur approximately 1 km to the south-east of the dredge site.

Appendix Table 6 shows the distribution of size-classes of *Crepidula fornicata* in the deposits, together with the percentage frequency of occurrence of each size class. Clearly the populations were dominated by specimens of <20 mm although some much larger individuals were recorded at most stations. Size frequency histograms for the shell length of *Crepidula fornicata* for some typical stations are shown in Figure 6.6.1b.

The annual growth rate of Crepidula fornicata can be calculated using growth bands which are well-defined on the shell of this mollusc (see Plate 6.6.1); this allows some estimates to be made of the age of the different size classes recorded above. Determination of the age structure allows estimates to be made of annual production by this mollusc.

**Plate 6.6.1.** Shells of the American slipper limpet *Crepidula fornicata* showing annual growth bands. The specimens shown are between 4 - 5 years in age.

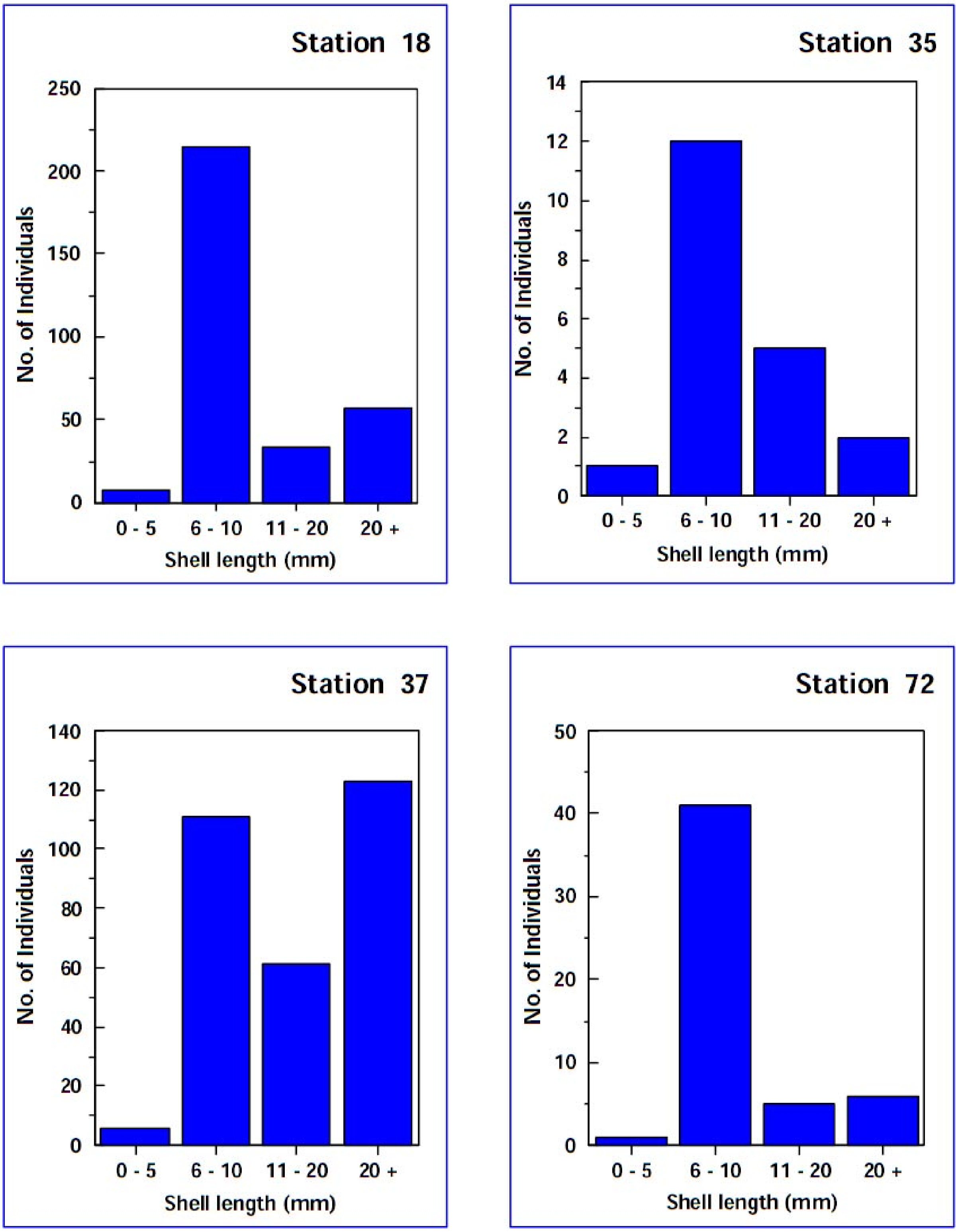


**Figure 6.6.1b**. Size-frequency histograms for shell length of *Crepidula fornicata* at Stations 18, 35, 37 and 72. Similar data for other stations at which *Crepidula fornicata* was recorded are summarised in Appendix Table 6.

Values for the shell size and age distribution in a series of 69 specimens of *Crepidula fornicata* are summarised in Appendix Table 7 and in Figure 6.6.1c.

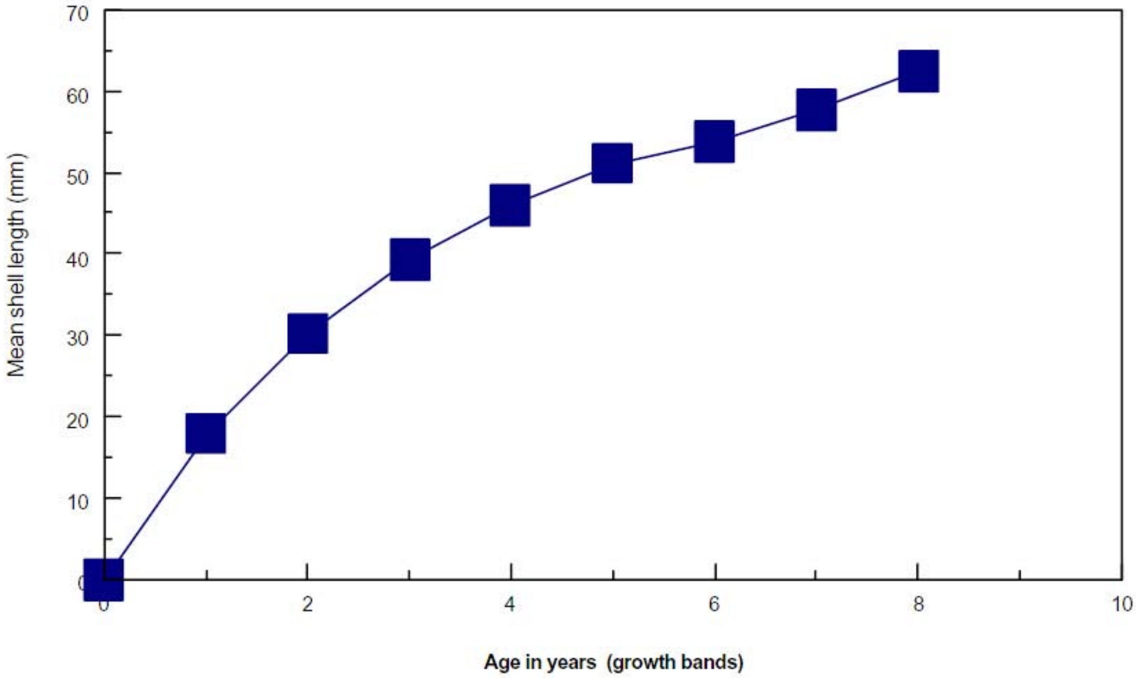


**Figure 6.6.1c.** Graph showing the relationship between the age of *Crepidula fornicata* established from shell growth bands, and mean shell length (mm). See also Appendix Table 7.

This shows that growth rate is initially rapid in the first 2-3 years, reaching a shell length of up to 30 mm. After this, growth rate decreases with the majority of the larger specimens attaining a shell length of approximately 50 mm at 6 years of age. A few specimens were recorded of up to 8 years of age. These data can be converted to tissue weight from the relationship between blotted wet weight of tissues and shell length. Text Table 6.6.1a shows the mean blotted tissue weights (g) for groups of *Crepidula fornicata* of differing shell lengths.

| Shell length (mm) | Mean wet tissue weight (g) | Standard deviation | N |
|---|---|---|---|
| 0-5 | 0.001 | - | 7 |
| 6-10 | 0.00791 | 0.0044 | 13 |
| 11-15 | 0.0288 | 0.0310 | 11 |
| 16-19 | 0.0396 | 0.0719 | 5 |
| 20-24 | 0.1496 | 0.0726 | 8 |
| 25-30 | 0.2723 | 0.0383 | 6 |
| 31-35 | 0.4633 | 0.2397 | 3 |

**Text Table 6.6.1a**. Table showing the mean blotted wet tissue weights (g) for groups of Crepidula fornicata of differing shell lengths (mm) from North Nab Study site.

These data are summarised in Figure 6.6.1d and can be used to calculate the incremental increase in tissue weight attained as a function of age in the slipper limpet.

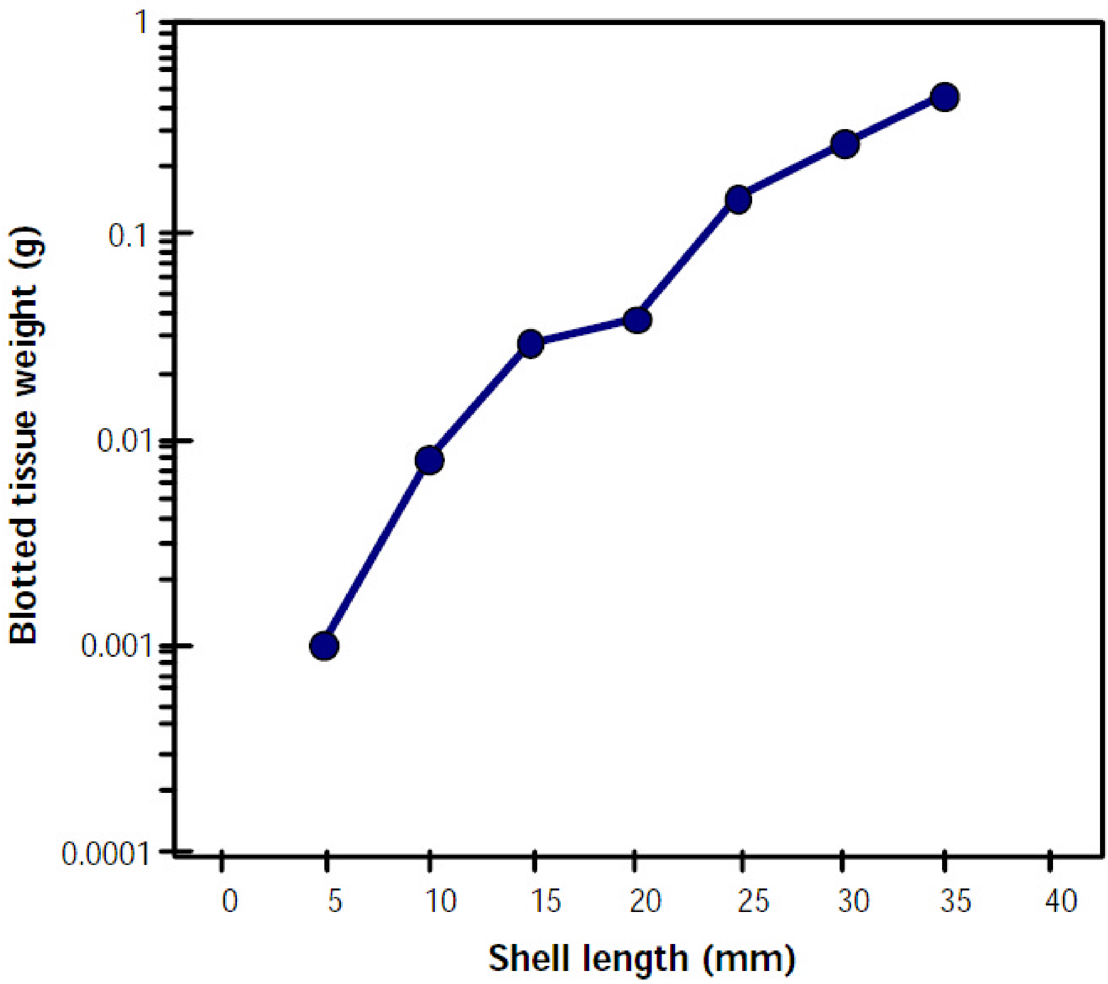


**Figure 6.6.1d** Graph showing the relationship between shell length (mm) of *Crepidula fornicata* and the blotted (wet weight) of tissues in grams. See also Text Table 6.6.1a.

### 6.6.2 Production Estimates for *Crepidula fornicata*.

Biomass and production values have been reported for *Crepidula fornicata* populations in the Bay of Marennes-Oleron, France by Deslous-Paoli (1980). He recorded an average yearly production of approximately 275 g per m² from a population of dry flesh biomass 583 g per m², the Production/Biomass ratio (P/B) being 0.46.

It is not possible to make any direct comparisons with the results of Deslous-Paoli (1980). However, some estimates can be made of annual production of *Crepidula fornicata* in the North Nab survey area by calculating the tissue weights of the Year 1 class, which correspond with shell lengths of 20 mm (Figure 6.6.1d). Appendix Table 8 shows the total number of individuals recorded at each of the survey stations at which *Crepidula fornicata* was recorded, and the number of specimens of <20 mm shell length (i.e. Year 1 individuals). The wet weight and AFDW in grams estimated from Eleftheriou and Basford (1989) are also shown in Appendix Table 8.

Text Table 6.6.2a summarises the number of *Crepidula fornicata* of shell length <20 mm (ascribed to Year 1 size class) and the number with a shell length >20 mm (ascribed to year classes 2 and 3). From Figure 6.6.1d, the biomass of Year Class 1 slipper limpets is the number of individuals x 0.05 g wet weight per 0.2 m². Equally the biomass equivalent of the Year 2 and 3 individuals of mean size 30 mm can be estimated from the number of individuals (N) x the mean wet biomass of 0.3 grams wet weight per 0.2 m². From Text Table 6.6.2a it can be seen that the average biomass of Year 1 *Crepidula fornicata* was 5.45 (s.d. 3.47) grams wet weight per 0.2 m² or 27.25 grams wet weight per m². The equivalent biomass in the larger size classes is 7.71 grams wet weight per 0.2 m² or 38.6 grams wet weight per m² and the total biomass estimated for all size classes is 13.16 grams wet weight per 0.2 m².

| Station | Year Class 1 (<20 mm shell length) | | Year Classes 2-4 (>20 mm shell length) | | Total Biomass g per 0.2 m² |
|---|---|---|---|---|---|
| | No. of individuals (*N*) per 0.2 m² | Biomass wet tissue weight (g) | No. of individuals (*N*) per 0.2 m² | Biomass wet tissue weight (g) | |
| 18 | 257 | 12.85 | 57 | 17.10 | 29.95 |
| 20 | 109 | 5.45 | 4 | 1.20 | 6.65 |
| 35 | 28 | 1.40 | 2 | 36.90 | 45.80 |
| 39 | 157 | 7.85 | 21 | 6.30 | 14.50 |
| 40 | 107 | 5.35 | 12 | 3.60 | 8.95 |
| 54 | 198 | 9.90 | 67 | 20.10 | 30.00 |
| 69 | 72 | 3.60 | 5 | 1.50 | 5.10 |
| 72 | 47 | 2.35 | 6 | 1.80 | 4.15 |
| 73 | 82 | 4.10 | 9 | 2.70 | 6.80 |
| 88 | 73 | 3.65 | 20 | 6.00 | 9.65 |
| 106 | 4 | 0.20 | 2 | 0.60 | 0.80 |
| 108 | 84 | 4.20 | 13 | 3.90 | 8.10 |
| 113 | 129 | 6.45 | 19 | 5.70 | 12.15 |
| **Mean** | **108.9** | **5.45** | **25.7** | **7.71** | **13.16** |
| **S.D.** | **69.47** | **3.47** | **34.3** | **10.29** | **12.99** |
| **N** | **14** | **14** | **13** | **14** | **14** |

**Text Table 6.6.2a.**Table summarising the numbers of slipper limpet *Crepidula fornicata* in Year Class 1 (<20 mm) and in older Year Classes (> 20 mm) per 0.2 m² in the North Nab Study site. The equivalent biomass has been estimated from the numbers of individuals (N) and the relation between shell length and wet tissue weight (Figure 6.6.1d)

The biomass achieved at the end of Year 1 by *Crepidula fornicata* is the annual production for that size class. Production at the end of Year 1 is therefore 5.45 grams wet weight per 0.2 m². The equivalent ash-free dry weight (AFDW) value is 5.45 x 0.085 (Eleftheriou and Basford, 1989) = 0.4633 g AFDW per 0.2 m² or 2.32 g AFDW per m².

Since carbon represents AFDW x 0.4 (see Mann, 1982) the carbon equivalent of production by *Crepidula fornicata* is equivalent to 0.89 grams carbon per m² at the end of year 1. Because the biomass of the larger size classes are similar to those for Year 1 individuals, the annual production by *Crepidula fornicata* in the North Nab site is likely to be approximately 1.8 grams carbon per m² per year in parts of the survey area where this mollusc is common.

This value may be compared with annual production estimates for benthos in the North Sea of 0.7 g carbon per m² (Buchanan and Warwick, 1974) and 2.7 grams carbon per m² for the Baltic (Cederwall, 1977) (see Text Table 6.5a).

The inference is that production by the slipper limpet (*Crepidula fornicata*) is alone comparable with that for typical total benthic production reported for coastal sediments elsewhere. When the contribution of other components of the benthos including dense communities of Bryozoans (notably *Flustra* spp), hydroids and other components are added, production by the benthos surrounding the dredge area is likely to considerably exceed that recorded for offshore sediments in the North Sea and Baltic Sea.

### 6.7 Impact of Dredging and Nature of the Recovery Processes

#### 6.7.1 Impact of Dredging on Species Diversity, Population Density and Biomass

In Section 6.2 of this Report, it was shown that the benthic community recorded in the sands that occur to the east of the survey area in the vicinity of the Nab Tower are relatively impoverished. Elsewhere in the survey area, the species diversity, population density and biomass of benthos are typical of those recorded by similar methods in coastal deposits in U.K waters (Text Table 6.1.2b). Surrounding the intensively dredged North Nab Production Licence Area 122/3 is an elongated zone or 'halo' of enhanced species diversity, population density and benthic biomass that corresponds with the main axis of dispersion of material from the worked deposits.

It is inferred that this zone of enhanced benthos could reflect the 17.36 tonnes AFDW organic matter estimated to be released per year in the outwash of dredgers operating within the restricted worked site in the North Nab Production Licence Area 122/3 (see Section 6.3). This material is likely to be carried beyond the boundaries of the Licence Area along the axis of dispersion by tidal currents and may be associated with "far field" effects of dredging outside the boundaries of the dredged area. The following Section focuses on the impact of dredging within the areas that are exploited by both anchor-dredge and trailer-dredging techniques.

#### 6.7.2 Impact on Population Density

Values for the population density expressed as number of individuals per 0.2 m² Hamon grab sample recorded at sampling stations in the vicinity of the dredged site within the North Nab Production Licence Area 122/3 are shown in Figure 6.7.2a.

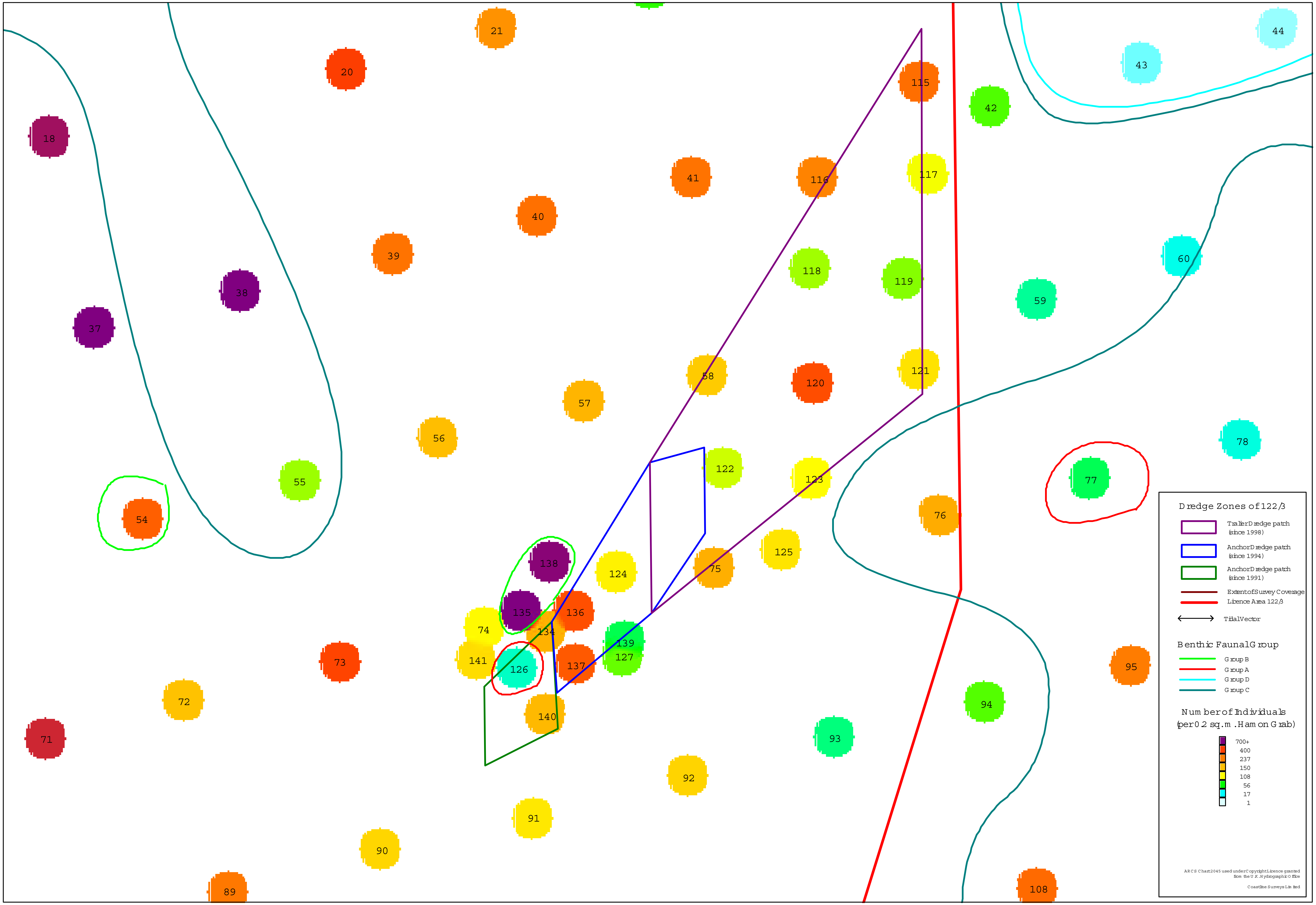


Figure 6.7.2a. Map of the intensively-dredged area showing a grid thematic map for the number of individuals of macrofauna (>1mm) per 0.2 sq.m. Hamon Grab.

Inspection of Figure 6.7.2a shows that a number of sampling sites were characterised by a low population density of marine invertebrates (see also Text Table 6.1.2a) Stations 124, 126, 127, 139 and to a lesser extent Stations 134 and 140 show a suppressed population density compared with the benthos in the surrounding deposits both within and outside the boundaries of the worked area. It can also be seen that there is some suppression of numbers of benthos at Stations 74 and 141 approximately 50-100 metres to the East of the marked boundary of the anchor-dredge area.

Inspection of Text Table 6.7.2a shows that each of the stations where a reduced population density of benthos has been recorded corresponds with zones where anchor dredging had taken place. It is clear therefore, that anchor dredging has a significant impact on population density of the benthos, although the exact level of suppression recorded depends on whether our samples coincided with the middle of the dredge pit, and the number of days elapsed since dredging took place.

| Station # | Date sampled | Date last dredged | Days elapsed | Species (S) per 0.2m² | | Individuals (N) per 0.2m² | | Biomass (B) g AFDW | | Size (B/N) mg | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | No. | % | No. | % | g | % | mg | % |
| **Anchor Dredge** | | | | | | | | | | | |
| 126 | 13.03.99. | - | - | 11 | -62 | 26 | -87 | 0.257 | -83 | 1.0 | -86 |
| 134 | 08.06.99. | 01.06.99. | 7 | 21 | -28 | 166 | -16 | 0.606 | -61 | 3.6 | -49 |
| 141 | 08.06.99. | 21.02.99. | 107 | 22 | -24 | 130 | -44 | 0.149 | -90 | 1.1 | -84 |
| 139 | 08.06.99. | 18.12.98. | 178 | 21 | -28 | 44 | -88 | 0.037 | -98 | 0.8 | -89 |
| 124 | 13.03.99. | 06.04.98. | 312 | 10 | -66 | 114 | -42 | 0.964 | -38 | 8.5 | +21 |
| 137 | 08.06.99. | 15.07.98. | 355 | 26 | -11 | 330 | +69 | 2.106 | +36 | 6.4 | -9 |
| 136 | 08.06.99. | 09.05.99. | 395 | 33 | +13 | 357 | +82 | 0.170 | -89 | 1.5 | -79 |
| 140 | 08.06.99. | 25.11.97. | 560 | 20 | -31 | 153 | -22 | 0.258 | -83 | 1.7 | -86 |
| **Trailer Dredge** | | | | | | | | | | | |
| 118 | 13.03.99. | 21.02.99. | 20 | 25 | -14 | 84 | -57 | 0.594 | -62 | 7.1 | +1 |
| 122 | 13.03.99. | 23.12.98. | 80 | 31 | +7 | 60 | -69 | 0.235 | -85 | 3.9 | -44 |
| 123 | 13.03.99. | 23.12.98. | 80 | 30 | +3 | 105 | -46 | 0.301 | -80 | 2.9 | -59 |
| 121 | 13.03.99. | 21.12.98. | 82 | 18 | -38 | 124 | -37 | 0.196 | -87 | 1.6 | -87 |
| 120 | 13.03.99. | 19.12.98. | 84 | 25 | -14 | 358 | +83 | 2.100 | +36 | 5.9 | -16 |

**Text Table 6.7.2a.**Table showing the date at which a series of stations in the North Nab Production Licence Area 122/3 were sampled for macrofauna, when the stations were last dredged and the elapsed time in days. The number of species (*S*), number of individuals (*N*), and the biomass (*B*) (g AFDW) per 0.2 m², the body size (*B/N* mg) at each station is shown, together with the % reduction compared with average background values for all stations outside the dredge area shown in Figure 6.2.2.

From Text Table 6.7.2a, it can be seen that at Station 126 the population density showed an 87% reduction compared with average values for the survey area as a whole. This station is near a site that was being dredged at the time of our survey on 13.03.99, but we have no detailed record of when it was previously dredged, or whether disturbance by anchors has had an impact at this site. An 88% reduction in population density was recorded at Station 139 despite the fact that records from the dredger show that this site was last dredged 178 days prior to our survey. On the other hand, a reduction of only 16% in the population density was recorded at Station 134 despite the fact that records show that this station was dredged only 7 days previously (see Text Table 6.7.2a). This variability probably reflects the complexity of the seabed topography in the intensely worked anchor dredge site.

These data showing a variable reduction in the population density in dredged areas agrees with results reported in the literature for various sediment types (see Newell *et al*., 1998). A reduction of 70-80% in the number of individuals has been reported for commercially exploited sands and gravels (Désprez, 1992; van Moorsel, 1994). A smaller reduction of 46% was reported for sands in Moreton Bay, Queensland by Poiner and Kennedy (1984) and a value of 60% for sands in Hong Kong waters (Morton, 1996).

Clearly the level of discrimination is controlled partly by the distance between sampling stations in our survey grid. However Figure 6.7.2a shows that samples taken at stations within approximately 100 metres of the dredge sites show high population densities of benthos. The impact of anchor dredging on population density of benthic invertebrates does not therefore extend beyond approximately 100 metres from the anchor-dredge sites in a Licence Area where discharge of material from overboard screening is minimal.

### 6.7.3 Impact on Species Variety

Figure 6.7.3 shows a map of the species variety recorded in the vicinity of the intensively dredged part of North Nab Licence Area 122/3.

In this case, the species diversity at Stations 126 and 124 show a significant suppression of 62- 66%, despite the fact that up to 312 days had passed since this station had been dredged (see Text Table 6.7.2a).

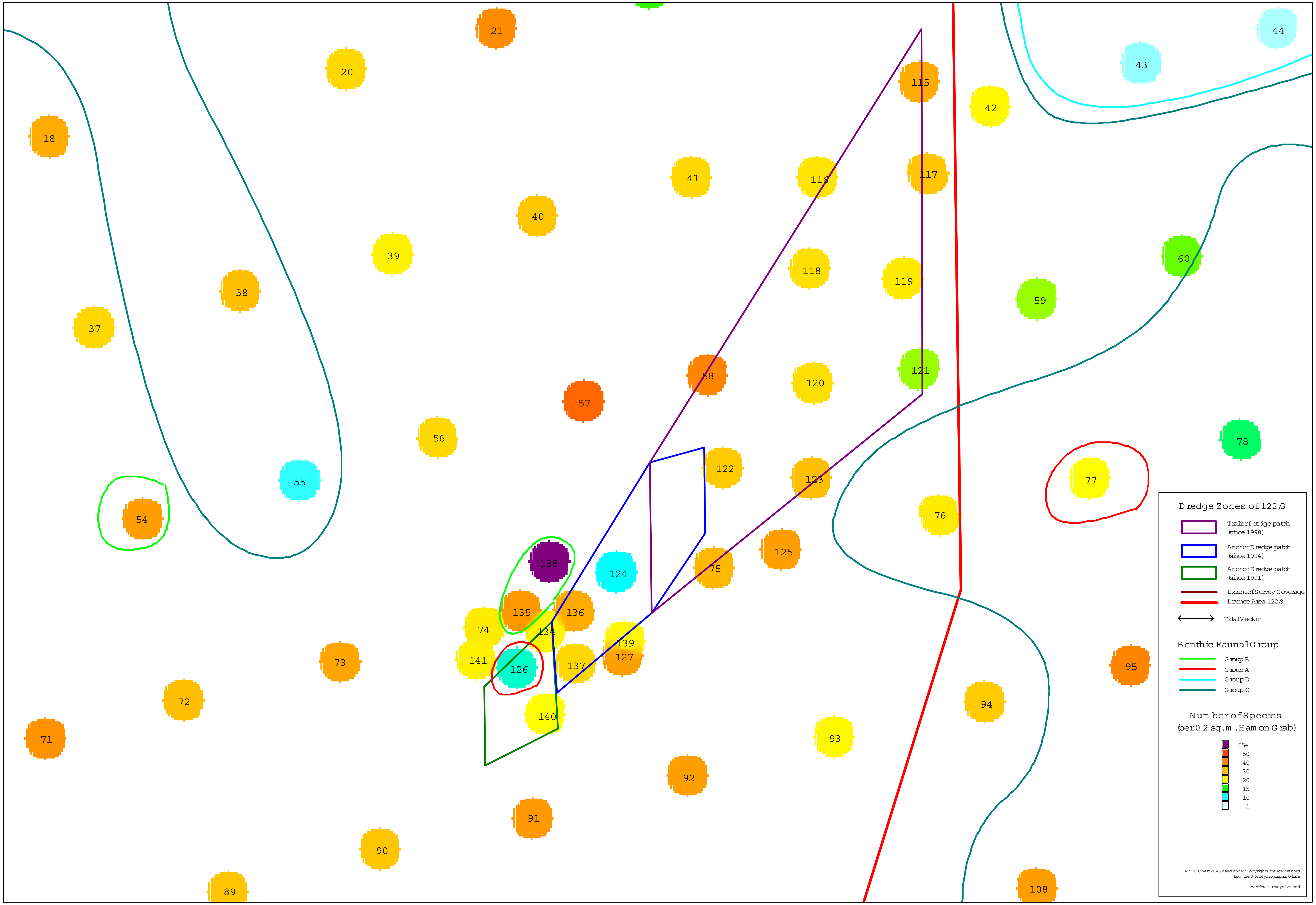


Figure 6.7.3. Map of the intensively-dredged area showing a grid thematic map for the number of species of macrofauna (>1mm) per 0.2 sq.m. Hamon Grab.

### 6.7.4 Impact on Biomass

The impact of anchor dredging on the total macrofaunal biomass is summarised in Figure 6.7.4a.

This shows that a large number of previously dredged sites remained low in biomass despite the fact that the population density (Figure 6.7.2a) and the species variety (Figure 6.7.3) had largely recovered. Inspection of Text Table 6.7.2 shows that a major suppression of biomass of 80-90% was commonly recorded in previously dredged sites. Further, it is clear that this suppression persisted for periods in excess of 18 months after cessation of dredging.

Figure 6.7.4b shows similar data for the molluscan macrofauna close to the sites of anchor dredging.

Again it is clear that the biomass of Mollusca are significantly impacted at previously dredged sites, even though Text Table 6.7.2a shows that some of these had remained undredged for over 18 months. A suppression of the biomass of long-lived and slow growing components of the macrofaunal community has been commonly reported following dredging (see van Moorsel, 1994; Newell *et al*., 1998; Désprez, 2000).

The corresponding data for the biomass of “miscellaneous” macrofaunal groups comprising *Bryozoa* (mainly *Flustra spp.*) and hydroids are summarised in Figure 6.7.4c.

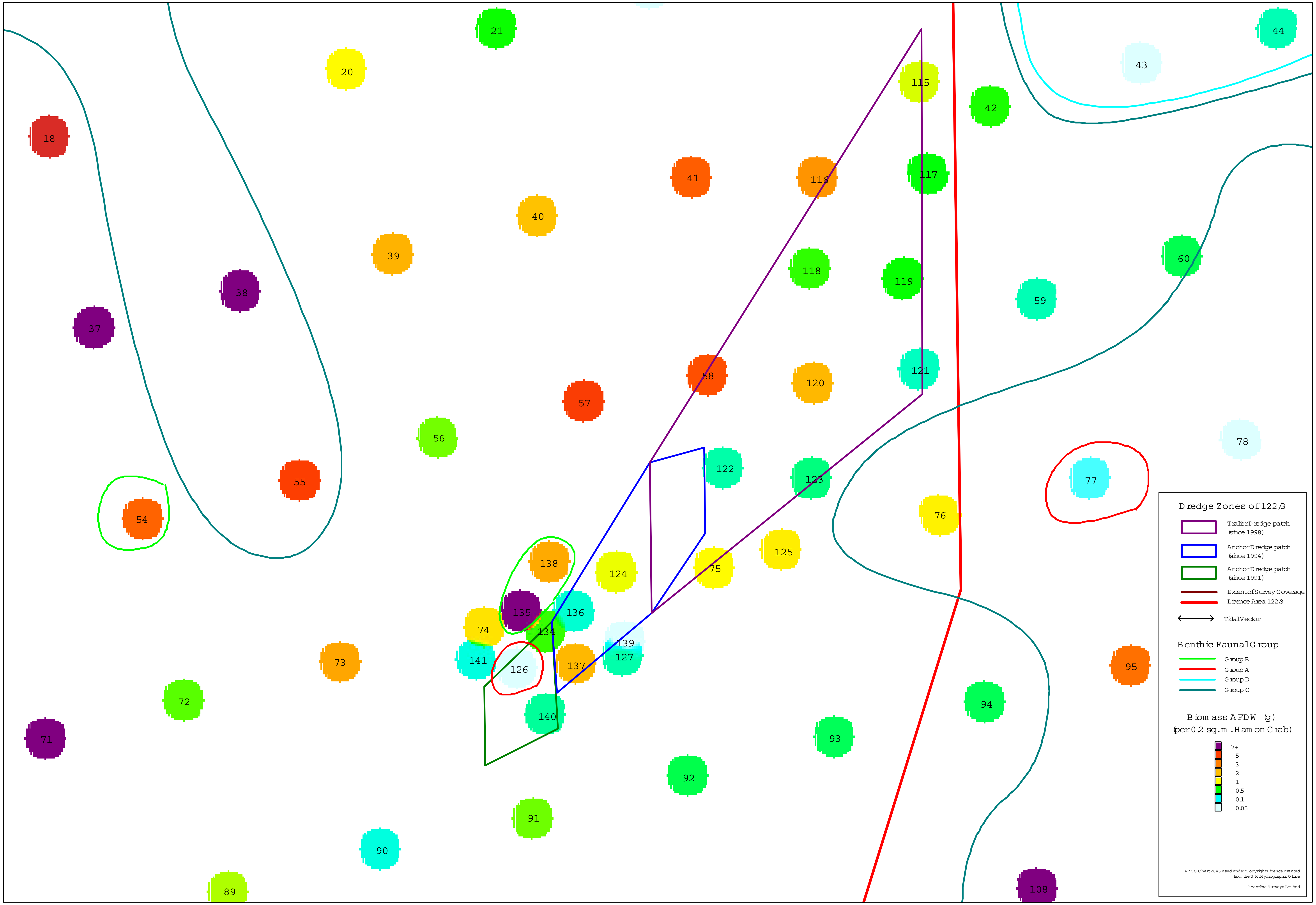


Figure 6.7.4a. Map of the intensively-dredged area showing a grid thematic map for the biomass (AFDW /g) of macrofauna (>1mm) per 0.2 sq.m. Hamon Grab.

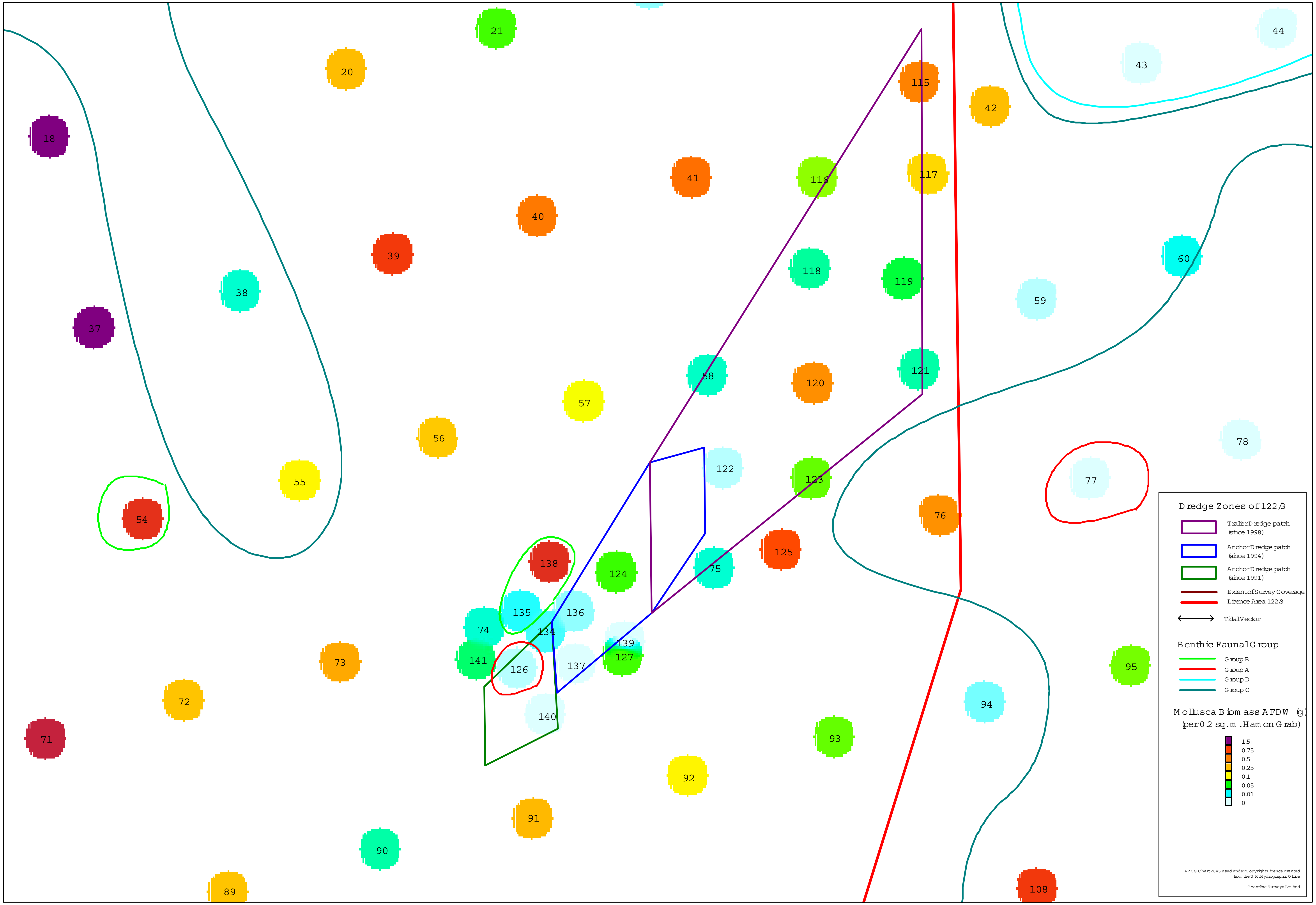


Figure 6.7.4b. Map of the intensively-dredged area showing a grid thematic map for the mollusc biomass (AFDW /g) per 0.2 sq.m. Hamon Grab.

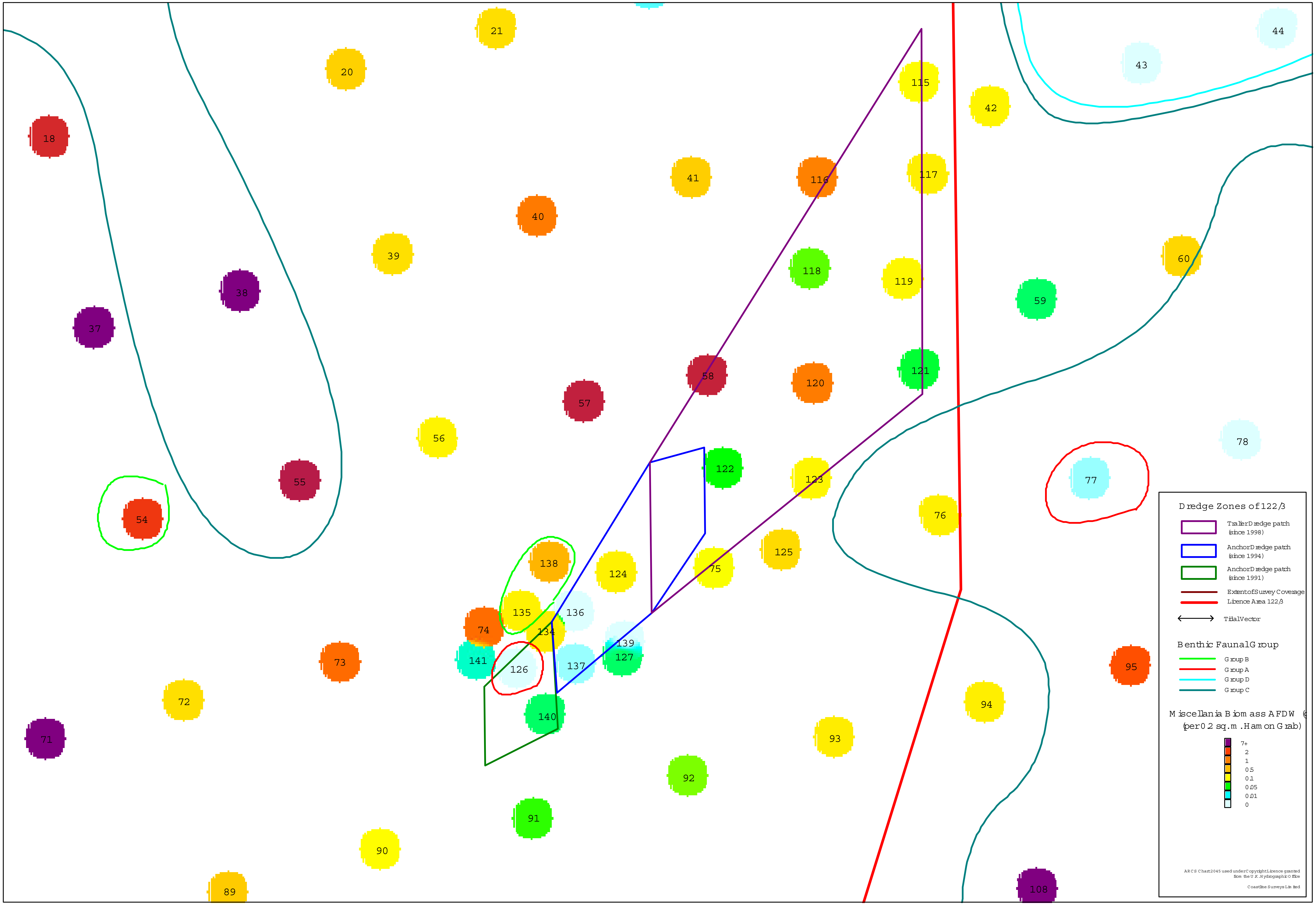


Figure 6.7.4c. Map of the intensively-dredged area showing a grid thematic map for the miscellania biomass (AFDW /g) per 0.2 sq.m. Hamon Grab.

### 6.7.5 Impact on Body Size

These data for species variety, population density and biomass of benthic macrofauna close to the sites of anchor dredging imply that after cessation of dredging initial recolonisation results in an increase in population density of typical species from the surrounding deposits. These species then increase in diversity as more species colonise the deposits; biomass is subsequently restored by growth of the individuals in the population once species composition has been largely restored.

Figure 6.7.5a shows a map of the average body size (B/N) of the macrofauna at each of the sampling sites within the anchor-dredge area. Restoration of the body size by growth of the colonising species is clearly far from complete at Station 136 after more than 395 days post-dredging (see also Table 6.7.2a). Again, there is some suppression of the size of the macrofauna at Station 140, more than 18 months after cessation of dredging.

These data for the time taken for restoration of biomass agree with those in the literature where recovery of the biomass after initial recolonisation by the macrofauna of sands and gravels has been reported to take 2-3 years (Désprez, 1992, 2000; Kenny and Rees, 1994, 1996; Newell *et al*., 1998). Figure 6.7.5b shows the relative rates of recovery of species variety, population density and biomass recorded by Désprez (2000) in deposits off Dieppe, France, following cessation of dredging in 1994. Species richness (S) and population density (N) evidently reached maximal values within 16 months of cessation of dredging. Biomass values, however, showed only a modest increase at 16 months, and continued to increase at 28 months after dredging had ceased.

These data show that critical stages in the recolonisation process, including an increase in species variety and population density, occur soon after cessation of dredging, but an increase in biomass following growth of the colonising species is achieved over a longer time.

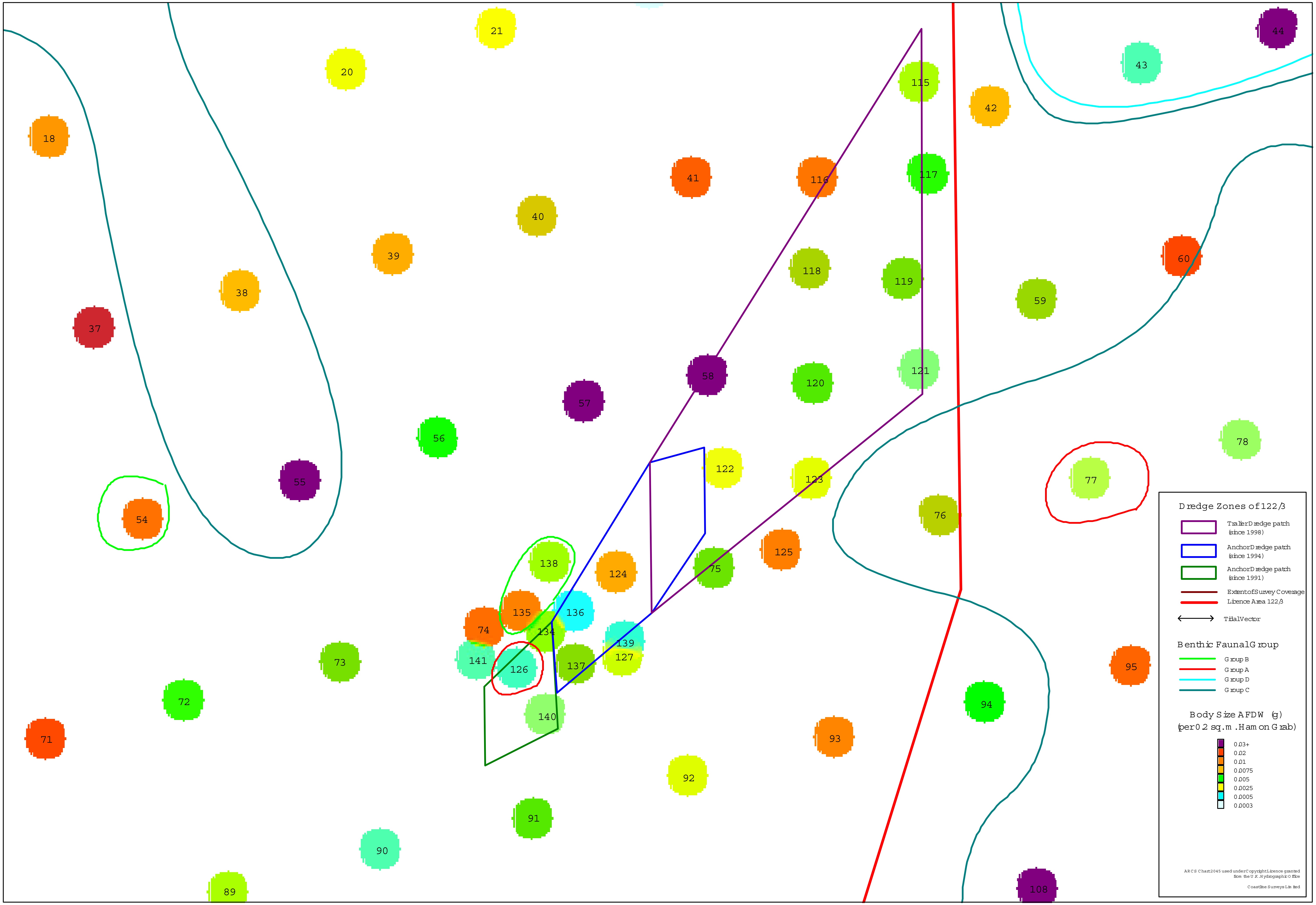


Figure 6.7.5a. Map of the intensively-dredged area showing a grid thematic map for the body size per 0.2 sq.m. Hamon Grab.

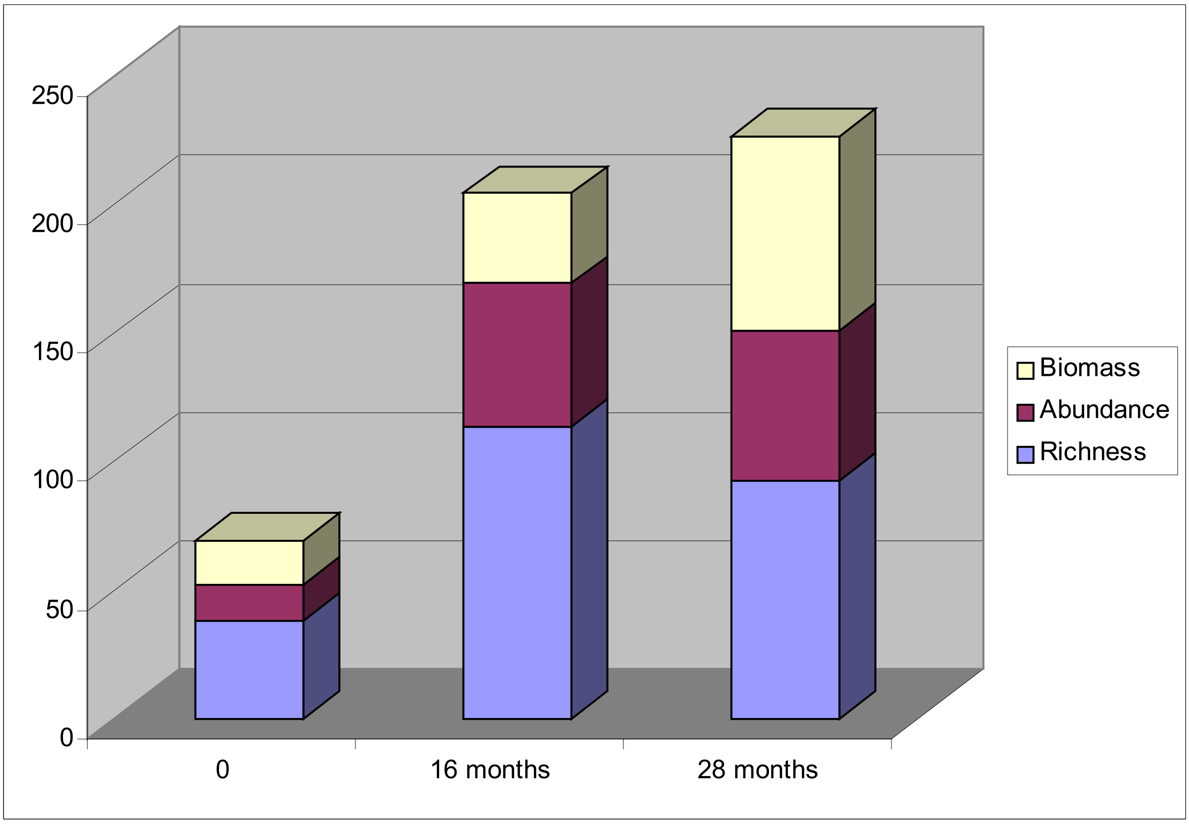


**Figure 6.7.5b** Diagram showing the rate of recovery of species richness, abundance (number per $m^2$), and biomass (g per m2) of benthic invertebrates following cessation population density and biomass recorded by Désprez (2000) in deposits off Dieppe, France, following cessation of dredging in 1994

## 6.8 Nature and Rate of Recovery Processes

These data show that anchor dredging has an impact on species variety, population density and biomass of benthic macrofauna within the boundaries of the dredged sites. Inspection of the records from the operating dredgers allows some estimates of the time course and sequence of recovery in the initial phases of the recolonisation process. Restoration of the species variety in the dredged areas to within 70-80% of that which occurs in the surrounding deposits occurs in 7 days after dredging at Station 134, and generally within 100 days at other stations. Restoration of the population density can also occur rapidly. At Station 134, for example, restoration of population density to within 86% of that in the surrounding deposits evidently occurred within 7 days. In general, the data summarised in Table 6.7.2 suggest that restoration of population density is achieved to within 60-80% of that in the surrounding deposits in approximately 175 days after cessation of dredging.

Finally, restoration of biomass by growth of the individuals is far from complete even after 18 months. A generalised flow diagram showing the sequence of recovery of the macrofauna in marine deposits based on the above data is shown in Figure 6.8.

Obviously the nature and rate of the recolonisation and recovery processes needs to be studied systematically at time intervals that reflect the rapid initial colonisation phase and the slower rates of increase in species diversity, population density and biomass. Inspection of Text Table 6.7.2a does, however, allow some comparisons between the rates of recolonisation and recovery in anchor-dredge sites with those in the trailer-dredge site to the northeast (see Figure 3).

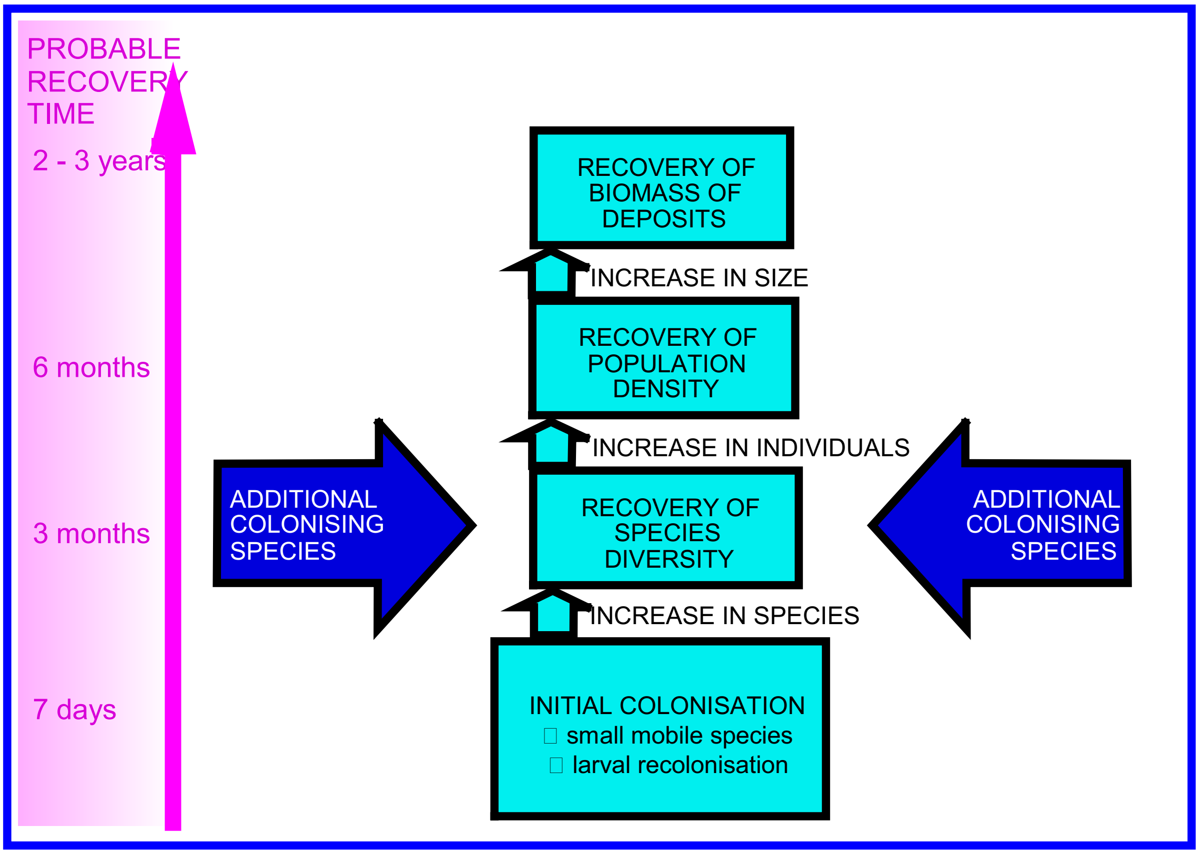


**Figure 6.8**. Generalised flow diagram showing the sequence of recolonisation and recovery in marine gravel deposits, based on the population density and species diversity in gravel deposits following known periods since the deposits were anchor-dredged.

Inspection of Text Table 6.7.2 shows that a recovery of 86% of the species diversity can occur within 20 days after trailer dredging, and that full recovery is achieved in approximately 80 days. Recovery of the population density to within 30-60% of that in the surrounding deposits is achieved within 80 days, but this is not significantly faster than that recorded in anchor-dredge pits. The biomass in general shows less than 20% recovery in a similar period.

The data for trailer-dredge areas suggest, therefore, that recovery of species diversity may occur somewhat faster within the narrow trailer-dredge tracks compared with the larger pits in the seabed associated with anchor-dredging. The time required for restoration of population density is not dissimilar to that for anchor-dredge sites. Finally, the biomass in trailer-dredge areas shows some recovery after 80 days but as in the case of anchor-dredging, is still suppressed by at least 80% compared with that in the surrounding deposits 80 days after cessation of dredging.

One of the problems encountered in analysis of seabed resources is that sampling of biological communities is often carried out under difficult conditions in sediments that show strong spatial variations in habitat type and associated community composition. Univariate indices of community composition such as species variety ($S$), population density ($N$), biomass ($B$) and indices such as body size ($B/N$) that depend on them show considerable variability. The ratio of 'noise-to-signal' in the data that is caused by sample-to-sample variability can then mask important indices of recolonisation and recovery such as those described above.

What is clearly needed, therefore, are systematic data on the recovery processes that are linked to what we now know to be the likely timing of the recovery processes and (importantly) for a sampling strategy to be devised that reduces sample-to-sample variability sufficiently to define recovery in anchor-dredge and trailer-dredge sites more precisely than we have been able to so far. The following section presents results that show the number of samples that are required to define species diversity in marine deposits, and the implications of this for marine environmental impact assessment and monitoring strategies.

## 6.9 Biological Diversity in Coastal Habitats

Appendix Tables 9, 10 and 11 show the species variety and abundance of individuals in three types of sediments identified by multivariate analysis of the deposits from the North Nab survey area. Appendix Table 9 summarises the data for the biota of sands and muds, Appendix Table 10 for the biota of coarse gravel and Appendix Table 11 the biota for gravels.

Figure 6.9a shows a series of 'Species Discovery Curves' for the macrofauna in the three types of sediments. The species in each of a series of samples of 0.2 $m^2$ have been plotted as a cumulative curve showing the additional taxa recorded in repeated replicates for each of the three types of sediment. The samples have been arranged in decreasing order of additional species discovered and can be used to determine both the total number of species that occur in each type of deposit, and the number of replicate samples that are required to provide a reliable estimate of species diversity.

Inspection of Figure 6.9a shows that the total number of species, as judged from the point at which no further taxa were discovered despite further replicate samples, was 82 in the sands and muds of the survey area. The corresponding value for coarse gravel was 185 taxa and that for the other gravel deposits was as high as 215 taxa, probably reflecting the habitat complexity of gravels compared with sands and muds. The total number of taxa in the deposits is therefore linked to the types of substratum in the survey area.

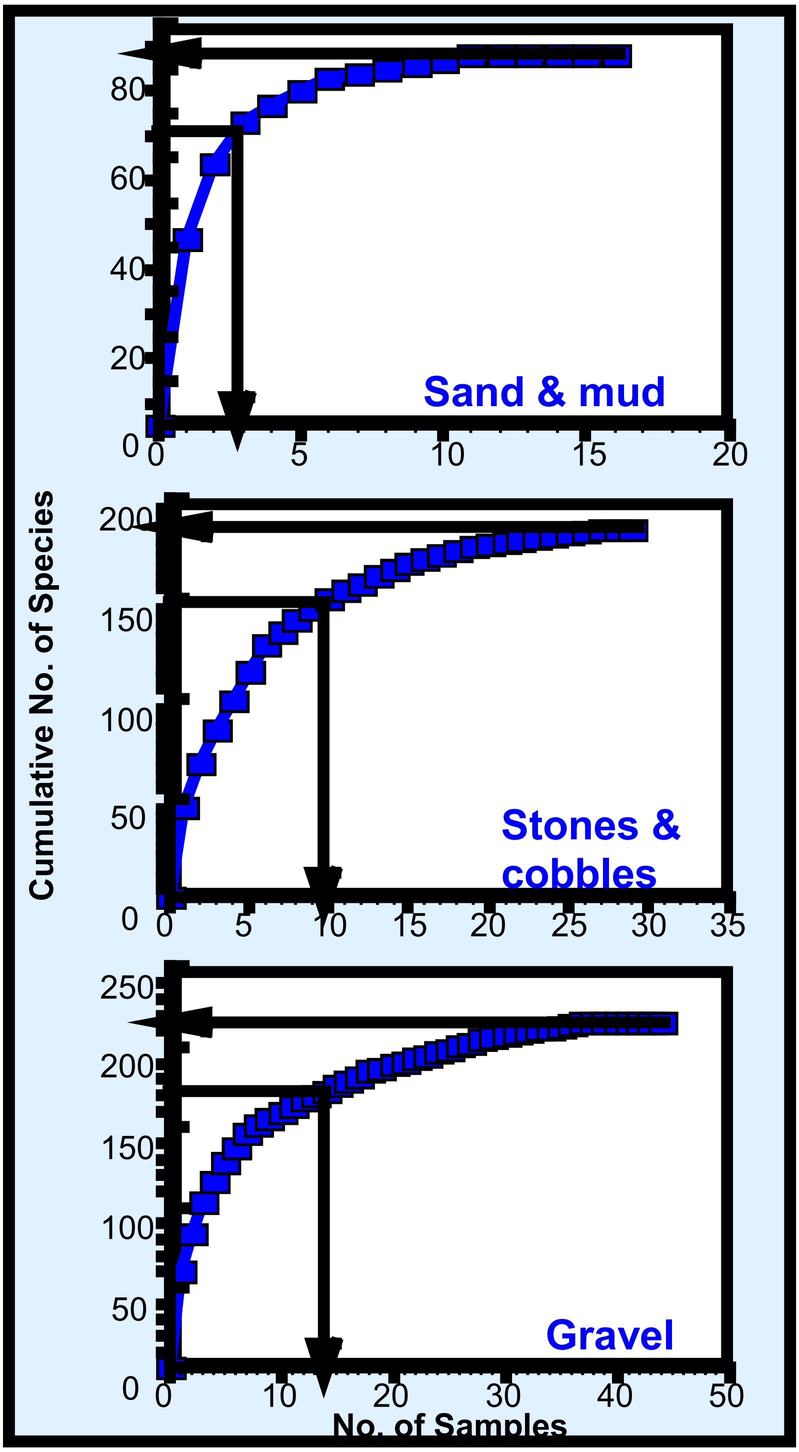


**Figure 6.9a.** Species discovery curves for the macrofauna in the three types of deposit recorded from the North Nab survey area in March 1999. The species recorded from a series of samples have been plotted as a cumulative curve showing the additional taxa recorded in a series of samples that comprise each of the three types of sediment. The total species complement and the number of samples required to establish 80% of the species diversity is indicated by arrows.

A second feature of interest is that the number of replicate samples required to identify at least 80% of the taxa that actually occur in the deposits is clearly related to sediment type. In the case of sands and muds that are dominated by one or a few taxa, only 2-3 replicate samples of 0.2 $m^2$ are required to discover at least 80% of the species present in the deposits, even if as many as 82 taxa are present. Similar results have been obtained for sands and muddy deposits off Folkestone, Kent by Newell *et al*. (2001). Where the deposits have a more even distribution and comprise a larger species variety as in the coarse gravel samples, up to 10 replicate samples are required to define 80% of the species present. Finally, in gravels of the survey area, at least 13 replicates are required to satisfactorily identify 80% of the taxonomic diversity of the sediments.

When sufficient samples are pooled to give a reliable estimate of species diversity, the data clearly show that dredging for marine aggregates at North Nab Area 122/3 does have an impact on the relative contribution of different species comprising the benthic biological resources. A k-dominance curve shows the relative contribution of each component species to the total species complement in the community. Dredged areas (coded green in Figure 6.9b) are dominated by one, or a few species compared with undredged deposits. Dredging therefore has an impact on the relative proportions of species in the community. The question arises whether this is imposed by anchor dredging, by trailer dredging, or is associated with both types of extraction of seabed deposits.

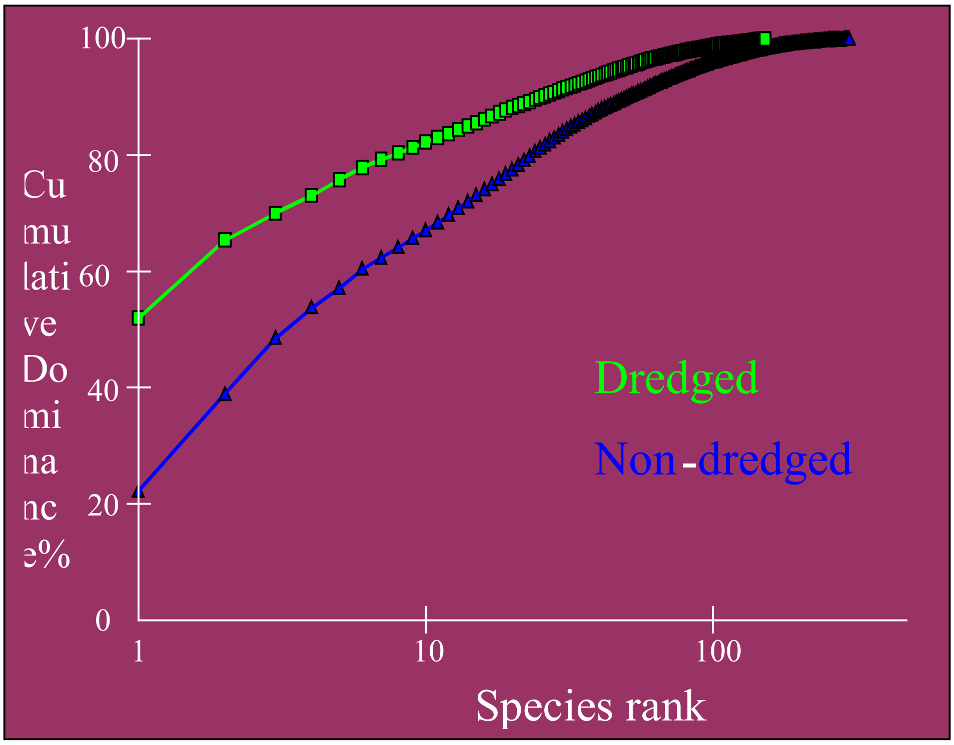


**Figure 6.9b.** Dominance curves plotted for pooled samples from dredged and non-dredged sites of Production Licence Area 122/3.

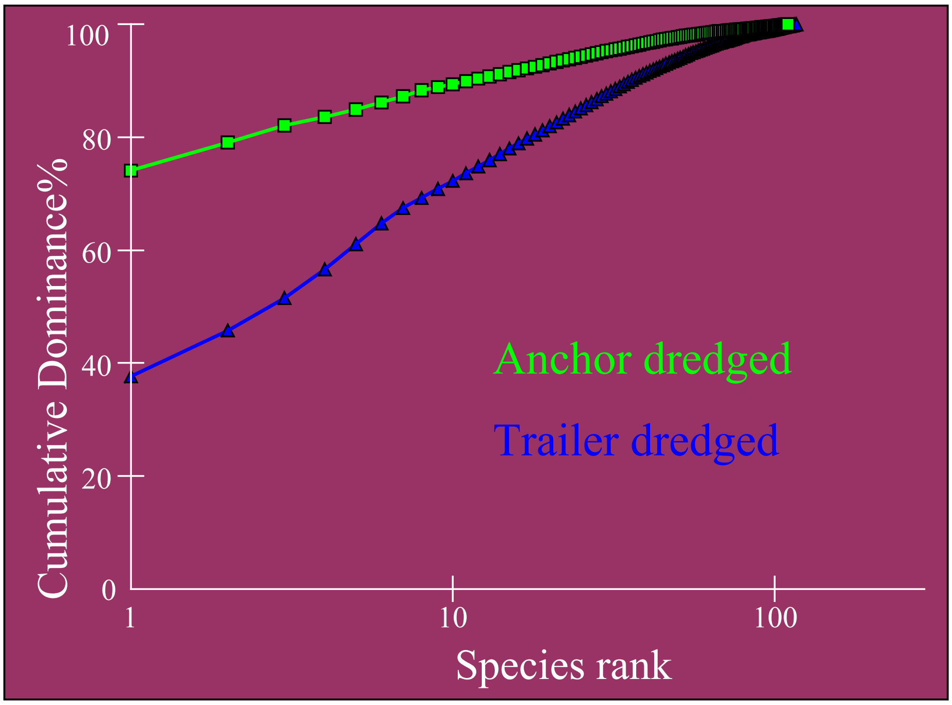


**Figure 6.9c.** Dominance curves plotted for pooled samples from within the anchor dredge site and within the trailer dredge part of Production Licence Area 122/3.

Figure 6.9c shows dominance curves plotted for pooled samples from within the anchor dredge site and within the trailer dredged part of Production Licence Area 122/3. The data show that anchor dredged sites are heavily dominated by one species (*Ampelisca* sp) whilst trailer dredged sites show a normal distribution of species composition. These differences account for the differing impacts of anchor dredging and trailer dredging on biological community composition identified by multivariate techniques (Figure 6.1.3c). Whether this is related to the type of dredging itself, or to differences in the relative intensity of dredging in the anchor-dredge and trailer dredging sites is at present unknown.

### 6.10 Implications for Sampling Strategies

Our results for the North Nab Production Licence Area 122/3 have implications for the spatial scale and frequency of marine monitoring programmes designed to assess the impact of marine sand and gravel mining, and the rate of recolonisation following cessation of dredging. We have shown that the principal impacts of dredging of non-screened cargoes are confined to the immediate dredge area itself. It has also been shown that for a non-screened aggregate mining area, far-field effects on benthic macrofauna may be associated with sedimentation of organic components in the outwash downstream from the dredge site. These occur mainly in an elongated 'halo' up to 3 km along the axis of dispersion of outwash on the ebb and flood tidal streams. This potential impact zone accords well with direct measurements of the morphology of dispersing plumes, including those from screened cargoes using acoustic backscatter methodology (Hitchcock and Drucker, 1996; Hitchcock *et al*., 1998; Newell *et al*., 1998, 1999).

The implication for marine monitoring surveys elsewhere is that the principal sites of impact of sand and aggregate mining is likely to be in the immediate vicinity of the dredge site, and for a distance of up to 3 km along the axis of the tidal streams, depending on the speed and direction of local currents. Sampling stations therefore need to be arranged relatively closely to define biological impact in relation to the dredge areas, the exact location and boundaries of which need to be defined with side-scan sonar at the time of the survey. Additional sampling stations then need to be arranged to define 'far-field' impact along the axis of dispersing material discharged from screening and hopper overspill, depending partly on the speed and direction of tidal currents in the discharge area.

In general, a survey zone extending at least 4 km on each side of a dredge site will be required to define the boundaries of potential 'far field' components of the outwash, and further sampling stations are advisable to establish background values downstream from the dredge site. With heavily screened cargoes, the indications from the plume monitoring are that this 'far field' component may extend as far as one tidal excursion by virtue of the near bed benthic plume extension discussed in Section 5.

The results for the North Nab study site also show that the statistical methods used to assess environmental impact have an important bearing on the number of replicate samples required to establish environmental impact of sand and aggregate dredging on benthic biological resources. Changes in community composition of benthic macrofauna in relation to environmental gradients, including disturbance by man, have been widely studied in the North Sea and U.K coastal waters in recent years. In many cases non-parametric multivariate analysis of community structure has revealed changes along gradients some distance from point sources of environmental disturbance whereas univariate indices are less sensitive (Gray *et al*., 1988, 1990; Warwick and Clarke, 1991; Dawson Shepherd *et al*., 1992; Clarke, 1993; Clarke and Warwick, 1994b).

Such work has also shown that many species within the benthic communities that occur in coastal muds, sands and gravels are interchangeable in the way that they characterise the community. Community composition required for multivariate analysis of community structure can therefore be adequately defined by analysis of only a proportion of the taxa present (Gray *et al*., 1988) or by consideration of higher taxonomic levels than species (Warwick, 1993; Somerfield and Clarke, 1995; Clarke and Warwick, 1998).

Clarke and Warwick (1998) have referred to this excess of taxa required for satisfactory definition of the structure of benthic communities as "structural redundancy". It may account for the fact that communities of macrobenthos (>1 mm) in a number of recent surveys of sands and gravels can be satisfactorily defined and separated by multivariate analytical techniques, despite evidence of serious under-sampling by conventional 0.2 $m^2$ Hamon grab techniques (see also Newell *et al*., 2001).

In contrast, univariate indices of community composition are generally strongly dependent on sample size. Such indices are often used to determine the changes in community composition that occur in relation to pollution gradients and have been used to define the nature and rate of recolonisation processes in our study of the North Nab site. They include the number of species (*S*), population density (*N*), biomass (*B*), body size (*B/N*) and common diversity measures such as evenness (*J*), diversity (*H'*) and richness (*d*). Because individuals of a species are rarely distributed randomly and are clustered often in relation to small-scale environmental variations, adequate sampling of the larger macrofauna may require larger samples and more widely-spaced replicates than smaller sized components of the benthos (Clarke and Green, 1988; Gage and Tyler, 1991; Grassle and Maciolek, 1992; Gray, 1994; Warwick and Clarke, 1995, 1996). The size of sample, number of replicates and number of individuals within the sample thus affects the univariate indices of community structure that are often used in interpretation of environmental disturbance on the benthos.

The implications of the results that have been presented for the North Nab survey area are that a decision needs to be made at an early stage in the monitoring programme on whether non-parametric multivariate analyses are to be used as a method for detection of environmental impact and recovery, or whether univariate analyses are preferred. If multivariate methods are to be used, then single samples with a 0.2 $m^2$ Hamon grab evidently yield sufficient information on population structure to separate macrofaunal communities, despite large sample-to-sample variability associated with under-sampling of the rich benthic communities of gravels with conventional grabs.

If, on the other hand, impact and recovery processes are to be monitored using single population variables such as number of species (*S*), population density (*N*), biomass (*B*) or body size (*B/N*), we have shown that as many as 10-12 replicates may be required to satisfactorily define 80% of the taxonomic diversity in marine gravel deposits. On pragmatic grounds it is probably then preferable to confine the number of sampling stations to a series along the axis of dispersion of outwash from the dredge site, and to avoid excessive 'noise to signal ratios' at those stations by ensuring that the number of replicates is sufficient to identify at least 80% of the taxa present.