Changes in Benthos Following the Clean-up of a Severely Metal-polluted Cove in the Hudson River Estuary: Environmental Restoration or Ecological Disturbance?

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ABSTRACT: We studied changes in macrobenthic communities following the environmental clean-up of metal-polluted (cadmium, nickel, and cobalt) sediments in Foundry Cove, a small inlet within the Hudson River estuary of New York. We used a BACI-style experiment to test the hypotheses that high levels of cadmium in sediments change macrobenthic assemblages relative to unpolluted areas, and removal of metals (especially cadmium) by dredging will restore the benthos, such that benthic fauna in Foundry Cove are not different from unpolluted areas. In 1984, prior to the restoration work, there were no significant differences between macrobenthic assemblages in polluted and unpolluted locations, indicating that cadmium had little effect on community structure. The lack of an observed toxicity effect may have been caused by the compensatory evolution of resistance to cadmium in dominant organisms. Six years after the restoration work and despite a substantial reduction in metal pollution, there were lower abundances of oligochaetes, nematodes, and chironomids and a higher abundance of polychaetes at Foundry Cove relative to reference locations. Correlative analyses identified greater sediment compaction caused by dredging at Foundry Cove as a possible cause of faunal differences. The results demonstrate that it is difficult to accurately predict the effects of anthropogenic disturbances and restorations in complex natural systems and that unforeseen side effects are inevitable. Documenting these unpredicted effects and experimentally understanding their causes in past restorations will greatly improve the success and cost-effectiveness of future projects of a similar type.

Introduction

Estuaries are ecologically and economically important ecosystems that support a range of commercial and recreational activities. The intensive use of these areas by humans has and will continue to have major impacts on estuarine systems (McLusky 1981; National Research Council 1995). While there has been an emphasis on protecting estuaries from further degradation (Good et al. 1999), there is an increasing number of large-scale projects aimed at restoring previously effected estuarine areas to a more natural state by creating new habitat (e.g., Craft et al. 1999), rehabilitating damaged habitat (e.g., Field 1998), altering tidal flow (e.g., Zajac and Whitlatch 2001) and removing toxic materials (e.g., Levinton et al. 1999). Although these projects are generally seen as a positive approach to estuarine management (National Research Council 1992), it is difficult to accurately predict all the ecological effects associated with these human manipulations in natural systems (e.g., Craft et al. 1999; Zajac and Whitlatch 2001).

Metal pollutants (lead, copper, cadmium, etc.) affect nearly all aspects of estuarine biota and, therefore, can be a major source of environmental degradation in estuaries (McLusky et al. 1986; Gray 1997). Although many countries currently legislate against further inputs of large quantities of metal pollutants into estuaries, past additions have established areas of high concentrations that can negatively affect ecological communities (McLusky et al. 1986; Somerfield et al. 1994). Eventually these metals are dispersed or buried by other sedimentary processes and are effectively removed from the biotic system (Advanced GeoServices Corporation 2001; U.S. Environmental Protection Agency [EPA] Authority 2002). This natural recovery may take decades or even centuries, over which time the ecological community may be changed permanently.

Removal of metals from estuaries could substantially speed up the natural recovery of polluted systems. There are very few ways to remove metals from submerged soft-sediment habitats apart from dredging the sediment that contains the pollution. Like toxic metals, dredging is also considered a major ecological disturbance because it alters productivity, sediment characteristics, and the diversity and abundance of benthic organisms (Rosenberg

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1977; Desprez 2000; Lewis et al. 2001). Managers of polluted estuaries are left with a conundrum when deciding the best course of action for dealing with toxic pollution in soft-sediment habitats. Such decisions will continue to remain difficult until there is good information on the effects of each of these environmental disturbances (pollution and dredging) and their interactions in a restoration context.

This manuscript focuses on the environmental clean-up of Foundry Cove, which was one of the most metal-polluted areas in the Hudson River system of New York. Foundry Cove was severely polluted by industrial waste discharged from a nearby factory that manufactured nickel-cadmium batteries from 1953 to 1979. The discharge included concentrated nickel and cadmium solutions, as well as cobalt, which was used as a stabilizer and discharged into the cove for a short period (Kneip and Hazen 1979). Since the concentrations of these metals are strongly correlated (Pearson's r 0.962, n 31, Klerks 1987), we will focus on cadmium, which is environmentally the most toxic (Klerks and Weis 1987; Savolainen 1995).

In total, 179 MT of cadmium was released into the environment, of which 53 MT was discharged directly into Foundry Cove and the rest into the main channel of the Hudson River (Resource Engineering 1983). The levels of cadmium in Foundry Cove sediments were extremely high, with much of the cove having concentrations in excess of 10,000 ppm (Knutson et al. 1987). Because cadmium is toxic to fish (Hansen et al. 2002), mammals (Szefer et al. 2002), and benthic invertebrates (Ahn et al. 1995; Hansen et al. 1996), it was expected that this extreme level of pollution would have serious and lasting effects on benthic community structure.

Qualitative comparisons in 1984, showed surprising similarity in richness and abundance of benthic fauna in Foundry Cove compared to a nearby unpolluted cove (Klerks and Levinton 1989a). Physiological investigations demonstrated that the high metal concentrations in the sediments were exerting toxic effects on the two major dominant groups of benthos, tubificid oligochaetes, and larval chironomid flies (Klerks and Levinton 1989b). In the case of tubificids, strong natural selection had caused rapid evolution of resistance to metals (Klerks and Levinton 1989b). If this evolutionary effect was pervasive throughout the community, then the similarity of benthic assemblages between the coves involved compensatory evolutionary change in resistance to metals in the Foundry Cove benthos, which may have forestalled major community reorganization owing to metal toxicity.

A lawsuit to force compliance with the U.S. Clean Water Act resulted in the removal of about 10% of the metals in 1972–1973, after which cadmium concentrations were still consistently greater than 10,000 ppm (Knutson et al. 1987). The cove remained badly polluted until a clean-up operation under the direction of the EPA Superfund project was completed in 1995. To remove metals from the badly polluted marsh, the area was completely dredged, a plastic membrane installed, clean fill added, and the marsh replanted. To remove the pollution from the open cove, the upper 30 cm of sediment were dredged and taken by rail to a landfill, with no replacement of sediment. The total cost of the project was in estimated to be 91 million U.S. dollars (EPA Record of Decision R02-89/97).

Using a BACI-style experimental design (see Underwood 1994 for review), we investigated the effects of metal pollution and its subsequent clean-up on the benthic community structure at Foundry Cove. We focused on macrofauna because they are important components of estuarine ecosystems (McLusky 1981; Levinton 1994) and are often sensitive to environmental disturbances (e.g., Rosenberg 1977; Olsgard and Gray 1995). Sediment-dwelling macrofauna are an important link in the trophic transfer of metals to commercially and recreationally important species of fish and crabs (Wallace et al. 1998; Rouleau et al. 2001). We tested the two hypotheses that the structure of benthic communities will differ between polluted and unpolluted coves prior to the clean-up, and removal of metal-rich sediments will restore the benthos, such that macrofaunal assemblages in Foundry Cove are not different from unpolluted areas. To gain insight into factors responsible for changes in the benthos, we tested for associations between macrofauna and environmental variables (concentration of metals, sediment, and organic matter characteristics) that are considered important determinants of community structure in soft-sediment habitats (see Snelgrove and Butman 1994 for review).

Materials and Methods

Study Sites

Foundry Cove is a tidal freshwater bay-marsh system approximately 87 km upriver of the mouth (The Battery, New York City) of the Hudson River (Fig. 1). It has a maximal tidal range of about 1.3 m and salinity varies from 0–6 ppt. Two relatively unpolluted bays, North and South Cove, were used as reference locations in this study. South Cove is located several kilometers downstream of Foundry Cove and had concentrations of cadmium less than 10 ppm prior to the restoration (Klerks 1987).

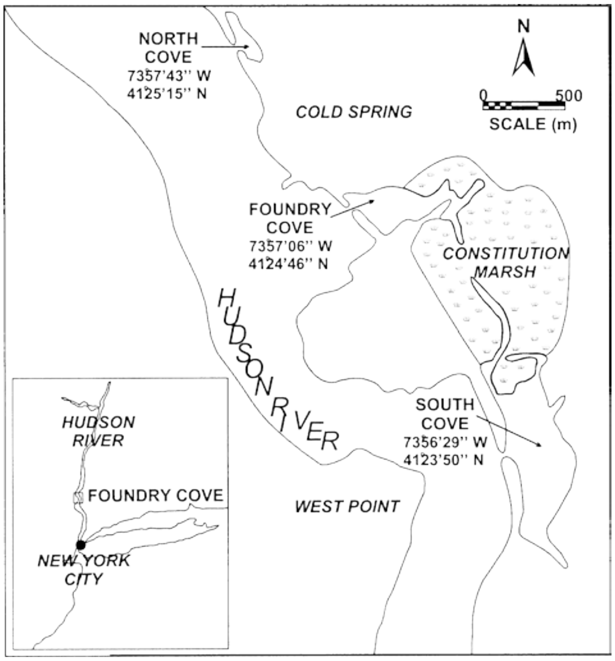

Fig. 1. Location of Foundry Cove relative to New York City and the reference coves.

Foundry and South Coves are separated by an extensive marsh system, which is currently a designated Audubon sanctuary (Fig. 1). North Cove is located several kilometers upstream of Foundry Cove. It is much smaller than the other two coves and is mostly surrounded by houses and playing fields, rather than extensive marshland. All coves are partially separated from the main body of the Hudson River by a railway trestle. For each cove, tidal flow to the open Hudson River is restricted to a small channel (Fig. 1). Each cove is almost completely flushed each tidal cycle by water from the main body of the Hudson River. It is likely salinity and water temperature were relatively similar in the different coves, although this was not quantified.

BENTHIC SAMPLING DESIGN

To investigate the effects of removing metal-rich sediments on benthic communities, sampling was done before and after the restoration work. Prior to the restoration, two polluted locations in Foundry Cove were sampled and compared to a reference location in South Cove (Klerks and Levinton 1989a). The concentration of metals in the sediments varied between the locations in Foundry Cove, with one having much higher concentrations than the other (FC_H 10,000 ppm Cd and FC_L 500 ppm Cd). Each location was sampled in June, August, October, and December of 1984. At each time of sampling and in each location, three sites were haphazardly selected about 10 m apart. In each site, 5 replicate cores (6.67 cm in diameter 5 cm deep, 175 cm^3) were collected.

Each core was washed in a 500 m sieve and the material retained was preserved in a 7% formalin solution. As well as macrofauna, the largest members of meiofuanal populations (e.g., nematodes, copepods etc.) were also retained using this mesh size. These smaller organisms were quantified and incorporated into analyses. It was understood that differences detected using this mesh size might not accurately represent changes in total abundance of meiofaunal taxa, but rather changes in abundances of the largest members of their populations. Locations were sampled again after the restoration using similar methods in May, August, October, and December of 2001.

Although the experimental design described above has adequate temporal replication, the lack of spatial replication at the level of locations can make interpretations difficult (Underwood 1994). To address this, spatial replication was increased in August and October of 2001 to include an extra location in South Cove and two extra locations in North Cove. At these times of sampling, the number of sites was increased from three to four to improve the power of tests of higher-level effects.

In the laboratory, the material from each sieved core was carefully sorted and macrofauna identified with a binocular microscope (16 magnification). In total, 30 taxa were found from 10 different Phyla (see Klerks 1987). The taxonomic resolution for the study was determined by the data collected in 1984 and was usually broader than species level. For soft-sediment macrofauna, it has been well established that the effects of anthropogenic disturbances can be reliably detected using higher-level taxa (Warwick 1988; Somerfield and Clarke 1995; Chapman 1998).

MEASUREMENT OF ENVIRONMENTAL VARIABLES

In October 2001, sediment was collected to evaluate the effects of restoration on levels of metal pollution and sediment characteristics and to test the hypotheses that these environmental variables (see below) influence benthic community structure. For these analyses, two extra cores (6.67 cm in diameter 5 cm deep, 175 cm^3) were collected from each site used in the benthic sampling and frozen at 80 C.

Prior to analysis of sediment, cores were thawed and homogenized. To determine concentrations of metals, a sub-sample of each core was oven dried for about 48 h at 60 C. For each core, approximately 1 g of sediment was digested using repeated additions of nitric acid (HNO_3) and hydrogen peroxide (H_2O_2). Cadmium and nickel concentrations in the digested sediment were then measured with graphite furnace atomic absorption spectophotometry (see Rivera-Duarte et al. 1999 for methods). To establish the amount of fine particles (silt/clay 63 m) in the sediment, approximately 50 g (dry weight) of each core was oven-dried at 80 C for 72 h, cooled in a desiccator, and weighed. Each sample was carefully washed on a 63 micron sieve and the remaining material dried (at 80 C), cooled, and weighed (as above). The proportion of fine particles was calculated by subtracting the amount retained on the sieve from the total weight. To determine the percentage of organic carbon and nitrogen, a sub-sample of each core was oven died at 60 C, ground into a coarse powder, and analyzed with a Carlo Erba NC soil analyzer.

In each site, the sediment compaction was quantified in the field with 20 randomly placed drops of a penetrometer (a steel rod 122 cm long, 1.22 cm in diam, 1.192 kg). For each replicate, the rod was dropped from 5 cm above the sediments surface and the depth penetrated measured.

Statistical Analyses

Analyses to investigate the effects of restoration on benthic communities were divided into balanced comparisons of data collected before and after the restoration and asymmetrical contrasts of Foundry and reference coves in 2001. The before-after analyses had four factors: comparisons before and after the restoration (2 levels, orthogonal and fixed); comparisons among the three locations, which were considered as treatments with varying level of cadmium (3 levels, orthogonal and fixed); comparisons among the four times of sampling nesting in the before-after term; and sites nested in the interaction of all other factors. Any effects of the restoration on the benthic assemblages should therefore be detected as an interaction between the before-after and treatment factor, rather than a main effect.

Analyses to test the hypothesis that benthic assemblages in Foundry Cove differ from those in reference coves also had four factors: comparisons among coves (3 levels, orthogonal and random), comparisons between August and October (2 levels, orthogonal and random), comparisons between the two locations nested in coves, and comparisons of sites nested in the interaction of all other factors. Because of the arrangement of random factors in these analyses, it was not possible to get an exact test for the main effects of coves. Rather than estimating denominators for *F*-ratios, asymmetrical comparisons about differences between Foundry and reference coves were made separately at each time of sampling. Analyses of environmental variables were similar to the ones used for benthic communities except there was no temporal component and data were pooled at the level of sites (n 24).

Hypotheses about taxonomic richness, abundances of major faunal groups, and environmental variables were tested with multi-factor analyses of variance (ANOVA). For analyses of abundances, distributions were often skewed and variances were mostly heterogeneous (Cochran's tests, p 0.05). Abundances were therefore transformed to ln (x 1) (Underwood 1997). Where appropriate, ANOVAs were followed by Student-Newman-Keul (SNK) tests to identify significant differences among means.

Hypotheses about differences in benthic assemblages were tested with non-parametric multivariate analyses of variance (np-MANOVA) (Anderson 2001a; McArdle and Anderson 2001). These analyses test for overall multivariate changes in community structure, which may include differences in composition, richness and individual species abundances. Non-parametric procedures were used because, similar to most studies on benthic communities, the data did not meet the assumptions of traditional multivariate analyses (e.g., MANOVA). Like other non-parametric multivariate methods (e.g., ANOSIM, Clarke 1993), np-MANOVA has less stringent assumptions than traditional multivariate tests. It improves on previous methods because it allows the direct additive partitioning of variation, which enables tests of multivariate interactions in complex experimental designs and asymmetrical comparisons. The test statistic (*pseudo-F*) is a multivariate analogue of Fisher's *F*-ratio and is calculated from a symmetric dissimilarity matrix. p-values are then obtained by permutation tests (see Anderson 2001a,b). Construction of these tests depends on the availability of permutable units in the denominator of each *pseudo-F* ratio and therefore varies according to terms in the model (Anderson 2001b). Here, the p-values for each term in the model were generated using 5,000 permutations and pair wise post-hoc tests were done on appropriate factors in each model. The significance levels of pair-wise tests were corrected using the Bonferroni technique. To graphically visualize multivariate patterns in benthic assemblages, non-metric multidimensional scaling (nMDS, Field et al. 1982) was used to produce two-dimensional ordination plots. All multivariate analyses were done using the Bray-Curtis similarity coefficient (Bray and Curtis 1957).

The BIO-ENV procedure (Clarke and Ainsworth 1993) was used to investigate relationships between macrofaunal assemblages and environmental variables. This technique correlates multivariate com-

TABLE 1. Post-hoc comparisons among locations in Foundry Cove with low (FC_L) and high (FC_H) levels of cadmium and a reference location in South Cove (SC) at each time of sampling before and after the restoration.

	(a) Faunal Community			(b) Oligochaetes			(c) Nematodes			(d) Polychaetes			(e) Gastropods		
Before															
June 1984	SC	FC_H	FC_L	SC	FC_H	FC_L	SC	FC_H	FC_L	SC	FC_H	FC_L	SC	FC_H	FC_L
August 1984	SC	FC_H	FC_L	SC	FC_H	FC_L	SC	FC_H	FC_L	SC	FC_H	FC_L	SC	FC_H	FC_L
October 1984	SC	FC_H	FC_L	SC	FC_H	FC_L	SC	FC_H	FC_L	SC	FC_H	FC_L	SC	FC_H	FC_L
December 1984	SC	FC_H	FC_L	SC	FC_H	FC_L	SC	FC_H	FC_L	SC	FC_H	FC_L	SC	FC_H	FC_L
After															
May 2001	SC	FC_H	FC_L	SC	FC_H	FC_L	SC	FC_H	FC_L	SC	FC_H	FC_L	SC	FC_H	FC_L
August 2001	SC	FC_H	FC_L	SC	FC_H	FC_L	SC	FC_H	FC_L	SC	FC_H	FC_L	SC	FC_H	FC_L
October 2001	SC	FC_H	FC_L	SC	FC_H	FC_L	SC	FC_H	FC_L	SC	FC_H	FC_L	SC	FC_H	FC_L
December 2001	SC	FC_H	FC_L	SC	FC_H	FC_L	SC	FC_H	FC_L	SC	FC_H	FC_L	SC	FC_H	FC_L

munity data with environmental variables to determine which variable or combination of variables best explains the community structure. For these analyses, a weighted Spearman's rank coefficient was used. Univariate patterns of association were tested using Pearson's r correlation coefficient (Winer et al. 1991). Because data were used for multiple comparisons, significant levels were adjusted using the sequential Bonferroni technique (Rice 1989). This method is less conservative than the standard Bonferroni technique, but ensures an appropriate type-I error rate is maintained.

Results

Comparisons of Benthos Before Versus After the Clean-up

The direction and magnitude of differences in benthic assemblages among treatments varied among the times of sampling, both before and after the clean-up (np-MANOVA, tr ti(ba) interaction, *pseudo*-$F_{12, 48}$ 2.60, p 0.001, permutable units 72 sites). Despite this, the patterns among post-hoc tests demonstrate that prior to restoration there was little difference between macrofauna in Foundry and South Cove in 1984, but large differences after the clean-up in 2001 (Table 1). These patterns were further supported by MDS plots (Fig. 2), which show overlapping assemblage structures of all locations prior to the restoration, but clear differences among fauna in Foundry and South Coves in 2001. Although there were significant differences in benthic macrofauna in two Foundry Cove locations in 2001 (Table 1), the dissimilarity between these locations was always less than between either one and the location in South Cove (Fig. 2). Consequently, the structure of benthic communities in Foundry Cove appears to have deviated from natural conditions after the clean-up. Furthermore, the large differences in levels of cadmium prior to the restoration appeared to have little influence on benthic community structure in 1984.

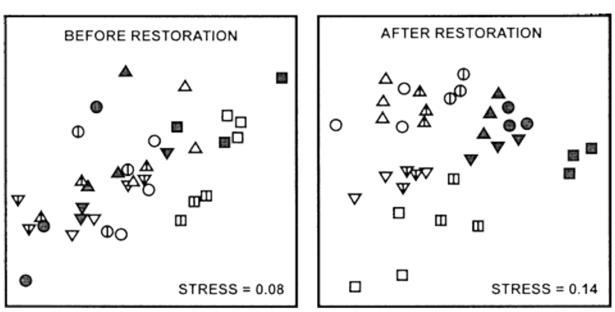

Fig. 2. Two-dimensional nMDS ordination plots comparing faunal assemblages in locations in Foundry Cove with low (open symbols) and high (open dashed symbols) levels of cadmium and a reference location in South Cove (grey symbols). Different shaped symbols indicate different times of sampling: squares May and June; inverted triangles August, triangles October; circles December. Each individual symbol represents the average assemblage at each site.

Similar to the benthic assemblages as a whole, there were consistent differences in the abundances of nematodes, oligochaetes and polychaetes that suggest the removal of metal-rich sediment altered the benthos relative to natural conditions (Fig. 3). Prior to the restoration, there were no significant differences in the abundances of any of these taxa between Foundry and South Cove locations. After the restoration, however, the abundances in South Cove were significantly different from those in Foundry Cove (Table 2; Fig. 3; see also interactions in Table 3). For oligochaetes in 2001, there was a decrease in Foundry cove relative to South Cove and relative to before the clean-up. In contrast, polychaetes were more abundant in Foundry than in South Cove in October and December of 2001. The abundances of nematodes were low in all locations in 1984, but the density increased in South Cove relative to Foundry Cove after the clean-up (Table 2; Fig. 3).

In contrast to multivariate measures, the taxonomic richness and abundances of chironomids and gastropods appeared to be relatively unaffect-

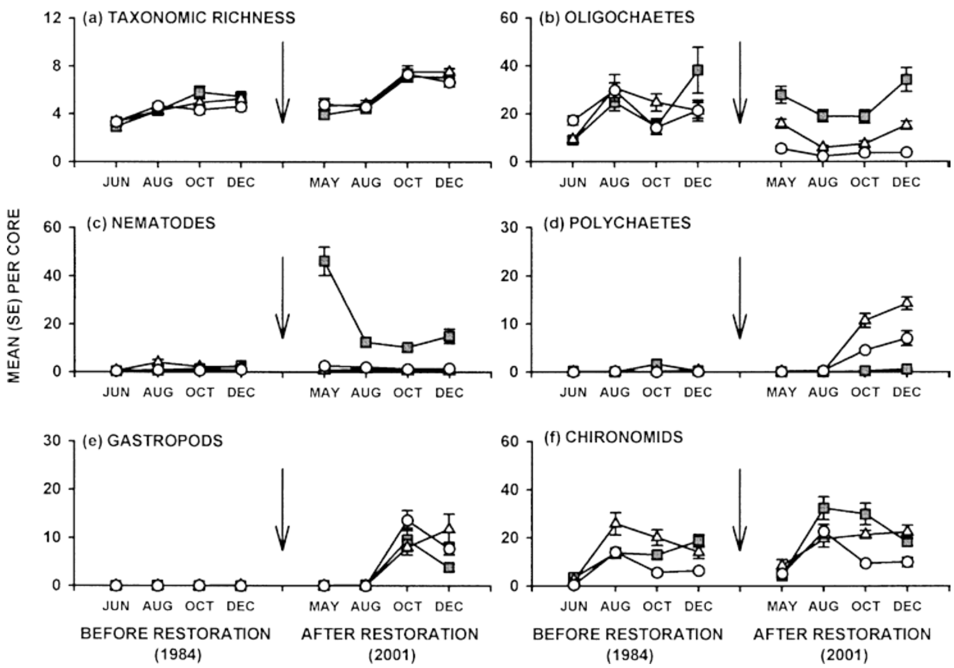

Fig. 3. Comparisons of mean (SE) richness and abundance of taxa in locations in Foundry Cove with low (open circles) and high (open triangles) levels of cadmium and a reference location in South Cove (grey squares).

ed by the clean-up, despite varying among times of sampling (Tables 2 and 3; Fig. 3). While the richness of taxa was remarkably consistent among locations, the abundances of gastropods and chironomids showed complicated patterns of spatial and temporal variation, but nothing consistent with a clean-up effect (Fig. 3).

Comparisons of Benthos in Foundry and Reference Coves After the Clean-up

In many respects, the analyses of sampling with greater spatial replication in 2001 support the interpretations of the before-after sampling. In both August and September, there were significant differences between benthic assemblages in Foundry

TABLE 2. Analyses of the richness and abundance of taxa (n 5). 'ba' is the fixed comparison between before (1984) and after (2001) the restoration; 'tr' is the fixed comparison among locations in Foundry Cove with low and high levels of cadmium and a reference location in South Cove; 'ti' is the comparison among times of sampling nested in the before versus after; 'si' comparison among sites nested in the interaction of treatments, times, and before versus after. Data for abundances were transformed by *x* ln (*x* 1).

		(a) Taxonomic Richness			(b) Oligochaetes			(c) Nematodes		
	df	MS	*F*	*P*	MS	*F*	*P*	MS	*F*	*P*
ba	1	211.60	2.70	0.152	27.35	4.54	0.077	54.93	10.82	0.017
tr	2	2.14	0.97	0.405	17.54	13.09	0.001	43.94	30.65	0.001
ba tr	2	4.23	1.92	0.188	33.53	25.02	0.001	53.30	37.18	0.001
ti(ba)	6	78.40	23.94	0.001	6.02	5.08	0.001	5.08	9.20	0.001
tr ti(ba)	12	2.20	0.67	0.769	1.34	1.13	0.359	1.43	2.60	0.010
si (tr ti(ba))	48	3.28	1.87	0.001	1.18	2.90	0.001	0.55	2.16	0.001
Residual	288	1.75			0.41			0.26		
		(d) Polychaetes			(e) Gastropods			(f) Chironomids		
	df	MS	*F*	*P*	MS	*F*	*P*	MS	*F*	*P*
ba	1	40.91	2.59	0.159	92.75	3.18	0.125	41.13	2.51	0.164
tr	2	8.02	2.41	0.132	0.63	1.08	0.370	17.73	8.99	0.004
ba tr	2	13.39	4.03	0.046	0.61	1.06	0.378	2.10	1.06	0.375
ti(ba)	6	15.79	63.27	0.001	29.17	116.46	0.001	16.36	15.28	0.001
tr ti(ba)	12	3.32	13.32	0.001	0.58	2.32	0.020	1.97	1.84	0.068
si (tr ti(ba))	48	0.25	2.54	0.001	0.25	1.70	0.005	1.07	2.85	0.001
Residual	288	0.10			0.15			0.38		

TABLE 3. Multivariate analyses of the macrofaunal assemblages in the three coves (co) sampled in 2001 (n 5). 'lo' is the comparison between locations nested in each cove; 'si' is the comparison among sites nested in each location. The 'co' term is divided into an asymmetrical contrast between reference locations (North Cove and South Cove) and Foundry Cove.

			(a) August 2001		(b) October 2001	
	df	Permutable Units	*pseudo-F*	*P*	*pseudo-P*	*P*
co	2	6 location units	5.37	0.006	6.64	0.002
NC, SC versus FC	1	6 location units	8.92	0.003	9.14	0.002
lo(co)	3	24 location units	3.36	0.002	4.63	0.003
si (lo(co))	18	120 sample units	1.59	0.005	1.61	0.004
Residual	96					

Cove and the reference coves indicating an effect of the clean-up (Table 3). These differences are also demonstrated by MDS plots, which show large separations between assemblages in Foundry and reference coves (Fig. 4). While there were no differences between benthic assemblages in North and South Coves in July 2001 (Post hoc test, p 0.05), macrofauna in these coves significantly differed in October 2001 (Post-hoc test, p 0.01). The dissimilarity between the references coves was much less than between either reference cove and Foundry Cove (Fig. 4).

At each time of sampling, there were significantly fewer nematodes and oligochaetes in Foundry Cove compared to the reference locations (Table 4; Fig. 4). In October, there were significantly more polychaetes and significantly fewer chironomids and gastropods in Foundry Cove relative to the reference coves (Table 4; Fig. 5). These results strongly indicate that the benthic community was affected by the clean-up process. Some caution is needed interpreting the responses of gastropod and chrionomids as a restoration effect because these results are not entirely consistent with before-after comparisons. Taxonomic richness did not differ in either before versus after comparisons or polluted versus unpolluted comparisons following the clean-up (Table 4; Fig. 5).

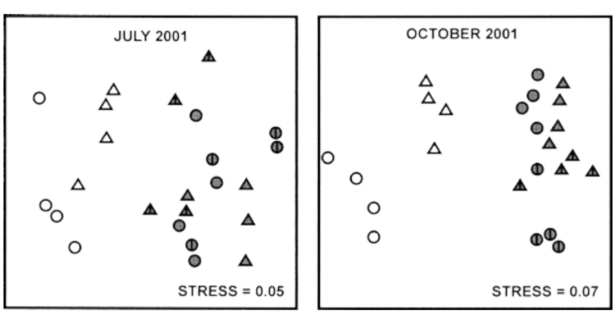

Fig. 4. Two dimensional nMDS ordination plots comparing faunal assemblages at the three coves sampled in 2001 (plain grey symbols North Cove; open symbols Foundry Cove; Striped grey symbols South Cove). Different shaped symbols represent the different locations nested in each cove and each individual symbol represents the average assemblage at each site.

Effects of Clean-up on Environmental Variables and their Relationships with the Benthos

The sediment in Foundry cove was significantly more compact (measured by the depth of penetration) than in either North or South Cove (Table 5; Fig. 6). The concentrations of cadmium and nickel, the percentage of fine particles and organic nitrogen and C:N ratio did not significantly differ between Foundry and reference coves following the clean-up (Table 5; Fig. 6).

Of six environmental variables, sediment compaction best explained the variation in the benthic assemblages in October 2001 (Table 6). The largest amount of variation was explained by the combination of sediment compaction and percentage of organic nitrogen, but the strength of this relationship was not substantially greater than just sediment compaction alone. Further additions of environmental variables in analyses weakened associations, demonstrating their lack of importance in determining macrobenthic community structure in this system.

After correction for multiple comparisons, there were few significant correlations between environmental variables and abundances of the major taxonomic groups in October 2001 (0.59 Pearson's r 0.59, n 24, p 0.002). The abundance of oligochaetes (Pearson's r 0.88, n 24, p 0.001) and chironomids (Person's r 0.78, n 24, p 0.001) were positively correlated to depth of penetration, whereas the density of polychaetes was significantly negatively correlated (Person's r 0.70, n 24, p 0.001).

Discussion

The restoration work at Foundry Cove was extremely effective in removing metal pollutants from the sediments. Prior to restoration, concentrations of cadmium in Foundry Cove sediment commonly exceeded 10,000 ppm (Knutson et al. 1987). The concentrations in 2001 were less than 10 ppm, which was the major criterion for restoration. Although the concentration of nickel was higher than cadmium, it was as expected given dif-

TABLE 4. Analyses of the richness and abundance of taxa in the three coves (co) sampled in 2001 (n 5). 'ti' is the comparison between the two randomly chosen times; 'lo' is the comparison between locations nested in each cove; 'si' is the comparison among sites nested in each location. The 'co ti' interaction is divided into asymmetrical contrasts between reference locations (North Cove and South Cove) and Foundry Cove at each time of sampling. Data for abundances were transformed by x ln (x 1).

		(a) Taxonomic Richness			(b) Oligochaetes			(c) Nematodes		
	df	MS	F	P	MS	F	P	MS	F_h	P
co	2	3.08	—	—	11.23	—	—	11.24	—	—
ti	1	490.20	95.57	0.010	0.09	0.34	0.617	0.28	26.76	0.035
(co) ti t1: NC, SC versus FC	1	1.20	0.09	0.779	14.78	29.42	0.012	7.64	13.56	0.035
(co) ti t2: NC, SC versus FC	1	5.40	0.42	0.563	8.04	16.01	0.028	7.61	13.51	0.035
lo(co)	3	6.10	0.48	0.721	0.99	1.96	0.297	0.32	0.57	0.671
lo(co) ti	3	12.84	4.00	0.015	0.50	6.25	0.002	0.56	4.23	0.012
si(lo(co) ti)	36	3.21	1.86	0.004	0.08	1.25	0.149	0.13	2.51	0.001
Residual	192	1.73			0.06			0.05		
		(d) Polychaetes			(e) Gastropods			(f) Chironomids		
	df	MS	F	P	MS	F	P	MS	F	P
co	2	4.71	—	—	3.66	—	—	1.50	—	—
ti	1	6.15	1.67	0.325	67.55	26.22	0.036	0.54	0.49	0.556
(co) ti t1: NC, SC versus FC	1	0.07	0.21	0.678	0.06	0.58	0.503	0.07	0.15	0.728
(co) ti t2: NC, SC versus FC	1	16.26	52.16	0.005	1.51	13.69	0.034	4.68	9.89	0.051
lo(co)	3	0.17	0.55	0.683	0.09	0.85	0.552	0.11	0.23	0.872
lo(co) ti	3	0.31	19.84	0.001	0.11	0.73	0.539	0.47	4.31	0.011
si(lo(co) ti)	36	0.02	0.97	0.526	0.15	2.38	0.001	0.11	1.71	0.012
Residual	192	0.02			0.06			0.06		

ferences in solubility coefficients between the two metals (Turner et al. 1992; Sanudo-Wilhelmy et al. 1996). Following the restoration, the concentrations of cadmium in benthic fauna, fish and birds at Foundry Cove also decreased (Advanced GeoSer vices Corporation 2001) and there was presumably a reduction in the export of metals into the main body of the Hudson River (Sokol et al. 1996). In many respects, the restoration work had a positive effect. In contrast to a priori predictions, the cadmium pollution did not have detectable effects on benthic community structure prior to the restoration, but its removal had a major impact on macrobenthos. Our study, demonstrates a number

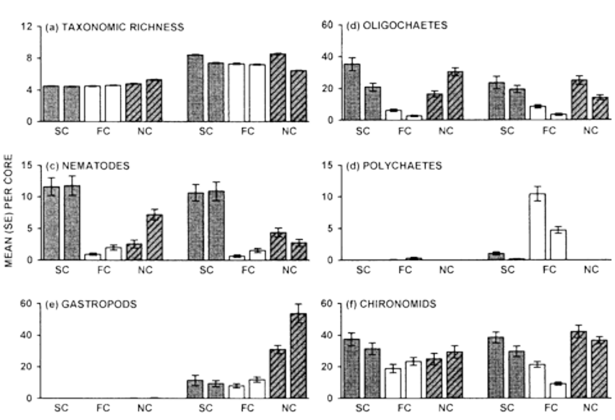

Fig. 5. Comparisons of mean (SE) richness and abundance of taxa in locations in the three coves sampled in 2001 (grey bars North Cove; open bars Foundry Cove; Stippled grey bars South Cove).

of unpredicted effects associated with the pollution and subsequent restoration of Foundry Cove.

Because cadmium generally has negative effects on benthic macrofauna (Ahn et al. 1995; Hansen et al. 1996), it was surprising that sensitive multivariate analyses did not detect differences between faunal communities in Foundry Cove relative to South Cove prior to the restoration. For these analyses, the numerically dominant taxa usually have the largest contributions to dissimilarity measures, especially when untransformed data are used (Clarke 1993). Much of similarities among benthic assemblages can be attributed to the spatial consistency in abundances of the most abundant taxa across locations. The abundant species (e.g., oligochaetes and chironomids), therefore, must have had effective biological mechanisms for dealing with metal pollution. Klerks and Levinton (1989a,b) demonstrated such a mechanism in the most abundant macrofaunal species in Foundry and South Coves, the oligochaete *Limnodrilus hoffmeisteri,* which could rapidly evolve a substantial resistance to cadmium. The lack of community level effects of cadmium pollution at Foundry Cove did not therefore preclude cadmium from causing changes in macrofauna at the genetic level (Levinton et al. 1999), which acted as a compensatory response to the toxicity.

Multivariate and univariate analyses detected consistent changes in benthic assemblages in Foundry Cove relative to reference coves after the restoration. In 2001, the abundances of oligochaetes were consistently lower in Foundry Cove.

between locations nested in each cove. The 'co' term is divided into asymmetrical contrasts between reference locations (North Cove and South Cove) and Foundry Cove.

	df	(a) Depth Penetrated MS	F	P	(b) Cadmium MS	F	P	(c) Nickel MS	F	P
co	2	371.99	6.15	0.087	15.27	1.99	0.282	9.41	0.43	0.688
NC, SC versus FC	1	741.24	12.25	0.039	20.65	2.69	0.200	8.66	0.39	0.576
lo(co)	3	60.53	18.76	0.001	7.69	6.92	0.003	22.13	2.43	0.098
Residual	18	3.23			10.72			9.09		

	df	(d) Fine Particles MS	F	P	(e) Organic Nitrogen MS	F	P	(f) C : N Ratio MS	F	P
co	2	169.50	5.20	0.106	0.0041	0.33	0.740	4.15	0.74	0.547
NC, SC versus FC	1	123.94	3.80	0.146	0.0081	0.66	0.478	3.06	0.55	0.513
lo(co)	3	32.61	0.70	0.562	0.0124	17.13	0.001	5.58	13.47	0.001
Residual	18	46.33			0.0007			0.41		

As the benthic communities developed with seasonal temperature increases, other differences between macrofauna (e.g., polychaetes and chironomids) in Foundry and adjacent coves also became apparent. These changes all strongly suggest a lasting ecological impact associated with the restoration work, considering samples were taken more than five years after the dredging was completed.

Similar conclusions can be made about changes in abundances of nematodes, although the form of these effects was different from other taxa. In 1984, there were low abundances of nematodes in all locations sampled. After the restoration, there was a natural increase in nematodes in reference locations, but no such changes in Foundry Cove.

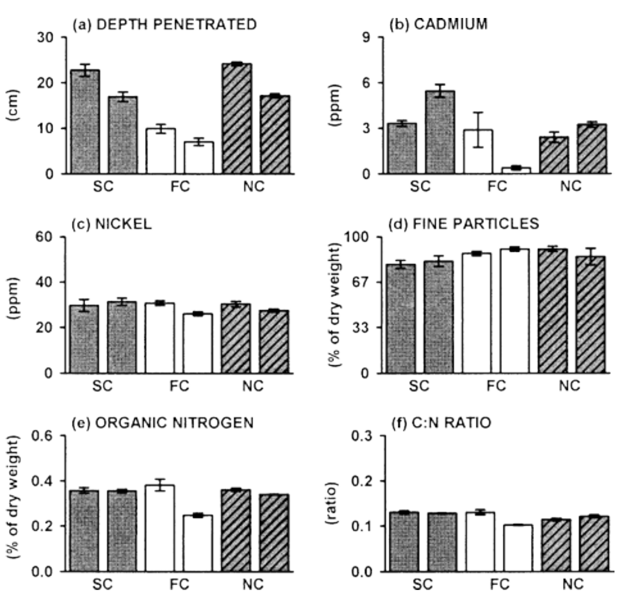

Fig. 6. Comparisons of mean (SE) environmental variables in locations in the three coves sampled in 2001 (grey bars North Cove; open bars Foundry Cove; Stippled grey bars South Cove).

The dredging appears to have altered natural changes in nematode abundances at Foundry cove relative to other places. Because large changes in abundances over time are common in most natural populations (Connell et al. 1997; Pearson and Mannvik 1998), careful consideration needs to be given to the design of sampling programs to assess environmental restorations to ensure that such changes can be sensibly interpreted relative to hypotheses being tested (Chapman 1999).

The changes in macrobenthic communities and especially the reductions of deposit feeders associated with the clean-up of metal-rich sediment are probably having a large impact on the benthic environment at Foundry Cove. Benthic deposit feeders accelerate the decomposition of particulate organic matter and increase microbial activity (Hargrave 1970; Rhoads and Young 1970; Lopez et al. 1987; Bianchi and Levinton 1981; Lopez and Levinton 1987). They also modify the physical and chemical characteristics of sediment and increase oxygenation of pore waters, which affects microbial community structure (Levinton 1994; Snelgrove and Butman 1994). Benthic macrofauna are often important components in food webs of commercially and recreationally important crustaceans and fish (Cote et al. 2001; Rijnsdorp and Vingerhoed 2001) and shorebirds (Baird et al. 1985).

Although a number of factors could have caused the changes in macrofauna in Foundry Cove after the restoration, alterations in sediment characteristics associated with dredging probably had a major contribution. The upper layers of sediment at Foundry Cove were more compact than the extremely soft mud found at the reference coves. Soft mud at Foundry Cove was probably removed by dredging, leaving sediment that had been compressed over many years. Compression of sediments can negatively affect benthic organisms (Kelaher et al. 1998; Evans et al. 1998) and, in this

TABLE 6. Correlation coefficients (n 40) for comparisons between macrobenthic community and combinations of environmental variables from BIO-ENV analyses. Values indicate the strength of relationships relative to the other comparisons. For brevity, only the best combinations for analyses with 2–6 variables are presented.

(a) Individual Characteristics		(b) Best Combinations	
Depth penetration (De)	0.546	De N	0.561
Nitrogen (N)	0.371	De N Cd	0.560
Cadmium (Cd)	0.331	De N Cd CN	0.541
C:N ratio (CN)	0.292	De N Cd CN Fp	0.510
Fine particles (Fp)	0.100	De N Cd CN Fp Ni	0.428
Nickel (Ni)	0.119		

study, was negatively correlated with oligochaetes and chrionomids. The increase in sediment compaction at Foundry Cove may have reduced foraging ability of many burrowing organisms, while increasing opportunities for surface feeding animals, such as the dominant polychaete *Hobsonia florida*. Dredging of estuarine sediments may also affect the proportions of silt/clay particles, which may in turn influence benthic community structure (e.g., Zajac and Whitlatch 2001). This was not the case for restoration work at Foundry Cove, however, because the percentage of fine particles did not differ among coves.

Because it can take years for restored marshes to function as efficiently as natural marshes (Craft et al. 1999), the simultaneous restoration of the marsh at the back of Foundry Cove may also be contributing to the reduced abundances of deposit feeding macrofauna in the main part of the cove. Marsh detritus is important sources of organic material for estuarine soft-sediments and this material often drives trophic interactions in the benthos (Levinton et al. 1984). The C:N ratio and bulk nitrogen in sediment can give only crude indications into the quality and quantity of food available for deposit feeders (Tenore 1983). Because these did not significantly vary among coves, it is unlikely that differential export of organic material is currently determining differences in benthic assemblages between Foundry and reference coves.

Colonization may also be major factor in the recovery of macrobenthic communities after disturbances (Levin 1984; Thrush et al. 1996). At the taxonomic resolution used in this study, all the taxa found in reference coves before and after the clean-up were also present in Foundry Cove in 2001. These results are encouraging because they indicate that the composition of the benthos at Foundry Cove is not limited by colonization and that through local population expansion a full recovery may be possible in time. At present, the restoration caused more faunal differences than did the presence of high concentration of cadmium prior to the clean-up. The evolution of resistance may therefore have been a powerful compensatory force to metal pollution, although such evolutionary responses may not occur in all cases (Klerks 2002).

Conclusions

As the major restoration criterion was the removal of cadmium from the sediments, the restoration at Foundry Cove was a success. Despite this, the restoration work also caused unpredicted changes in the benthos that are probably having negative effects on important ecosystem processes. Identifying the causes of these changes may improve the effectiveness of future restorations of similar type. With this in mind, our results indicate that experimentally investigating the role of sediment compaction in structuring macrobenthic communities and determining how compaction could be reduced (e.g., tilling or the addition of soft sediment) may be an important direction for future research.

It is difficult to accurately predict the effects of anthropogenic disturbances and restorations in complex natural systems and unforeseen side effects are inevitable. Accurately documenting such effects and determining their causes is the key to improving the success and cost-effectiveness of future restorations. This will only be possible if carefully designed monitoring programs and ecological experiments continue to be incorporated into the restoration process.

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