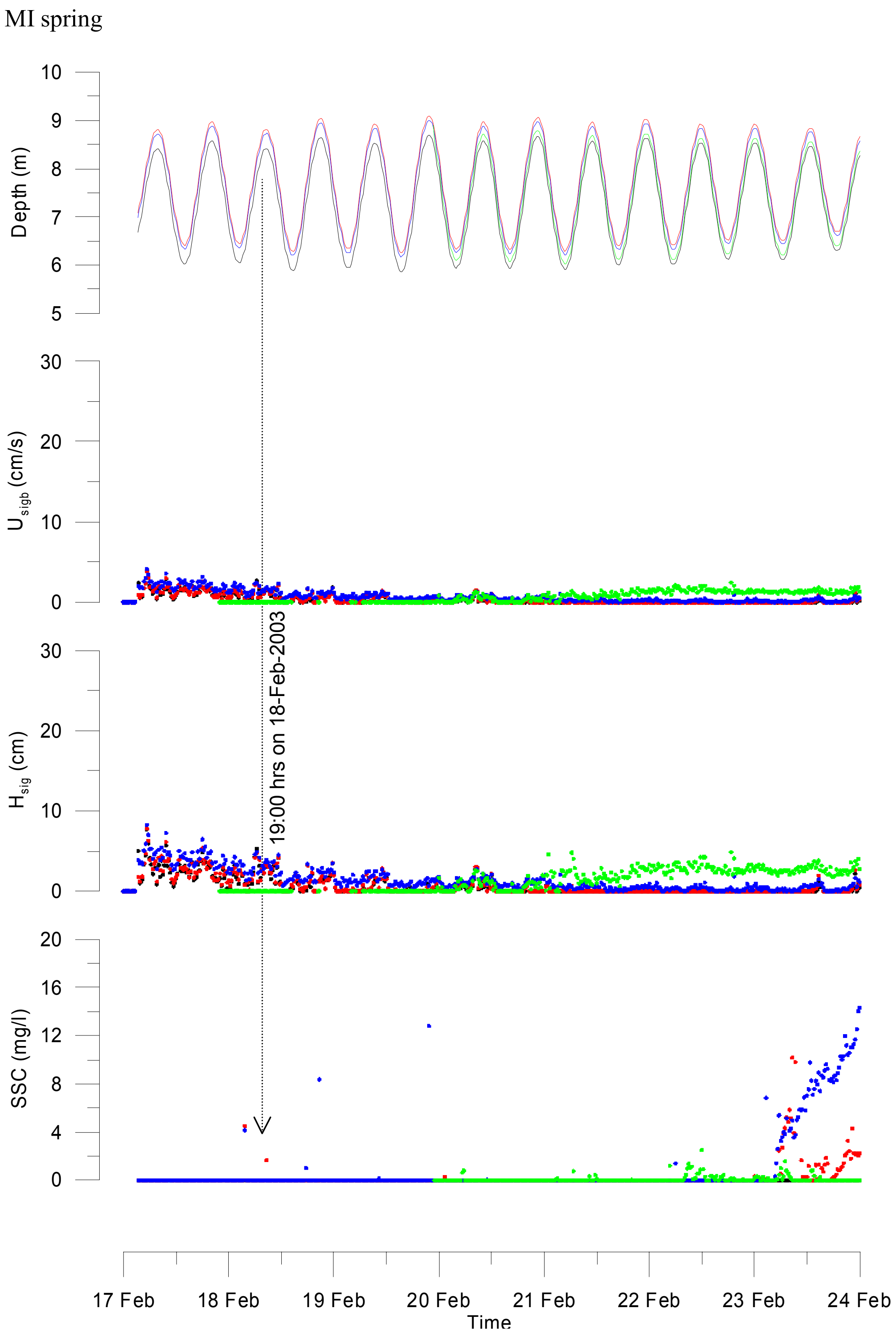


Figure 10: DOBIE-OBS data from Site MI early in the experimental period. Conditions were calm and average significant wave height (H_{sig}) and orbital bed velocity (U_{sigb}) values were small. There was very little suspended sediment measured (SSC=suspended sediment concentration) during this period. The dashed line with arrow indicates the first flooding tide following the application of terrigenous sediment at Site MI, when the terrigenous deposits were most likely to be advected off the plots and measured by the DOBIE-OBS. There was no such signal detected.

MI neap

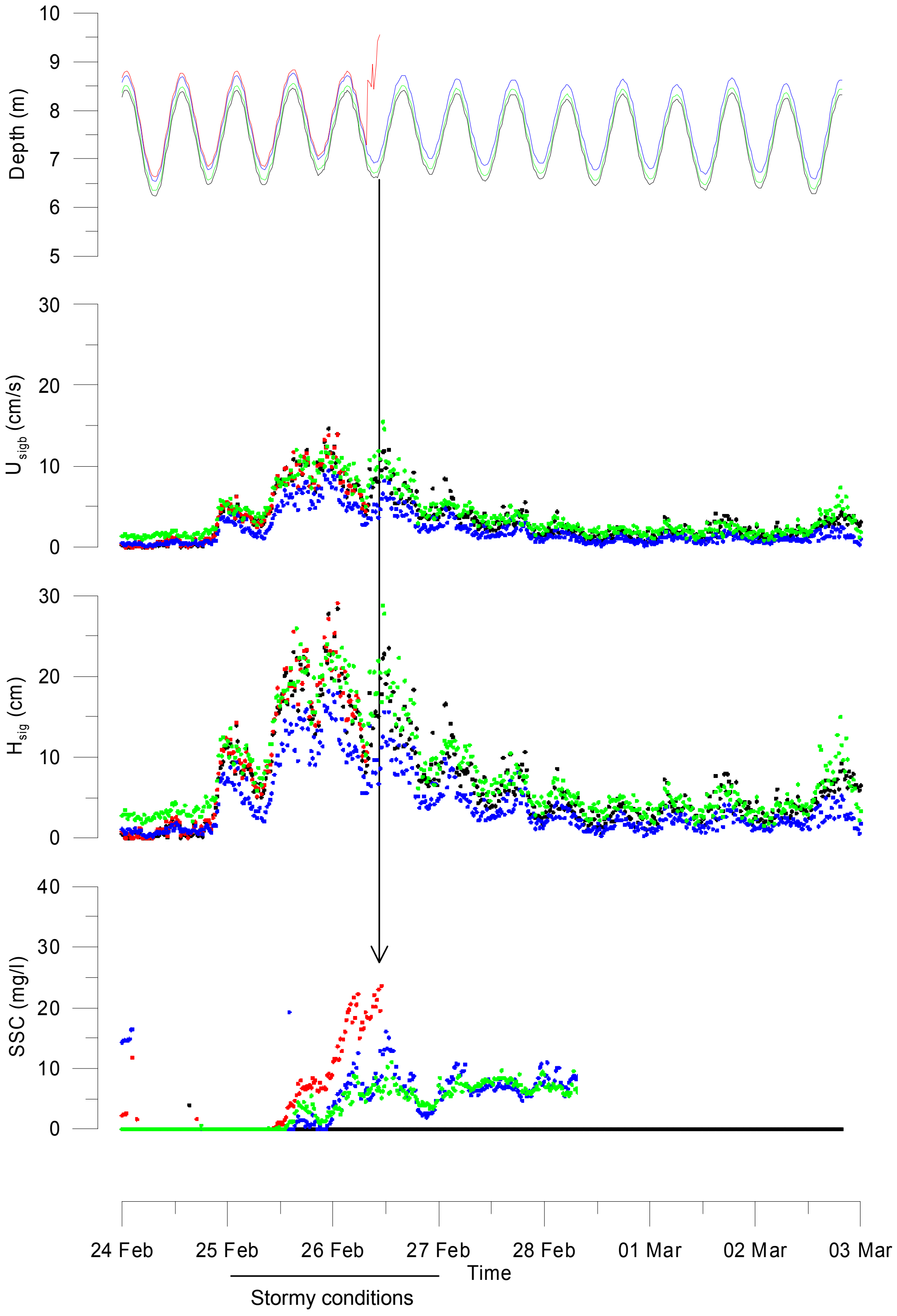


Figure 11: DOBIE-OBS data from Site MI, later in the experimental period. Day 7 at Site MI was 24-February-2003. During the storm, average significant wave height (H_{sig}), orbital bed velocity (U_{sigb}), and suspended sediment concentrations (SSC) all increased markedly. The peaks in each variable were coincident with high tides (see line with arrowhead). The data record for SSC is abbreviated due to problems of biofouling after 28-February.

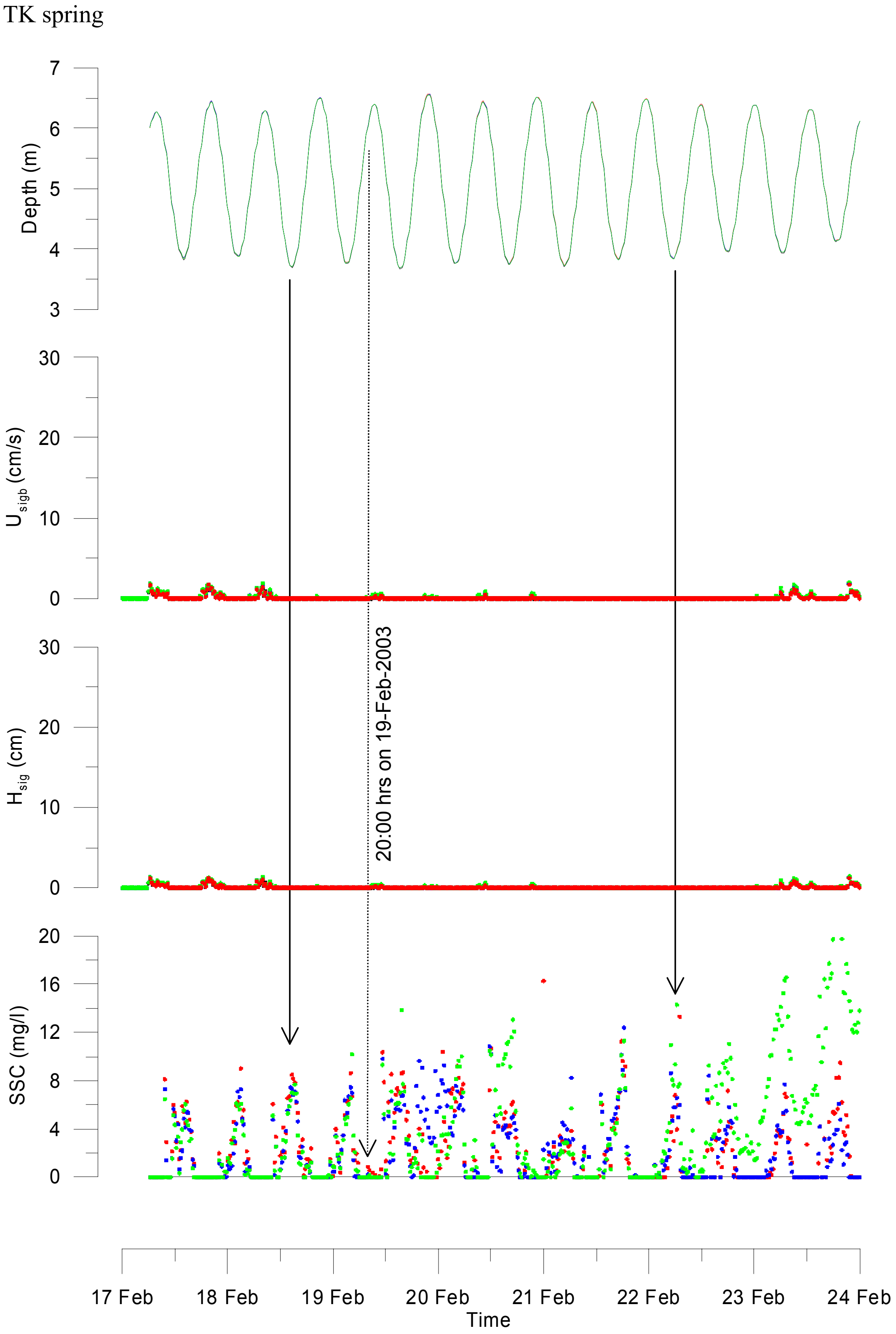


Figure 12: DOBIE-OBS data from Site TK early in the experimental period. Conditions were calm and average significant wave height (Hsig) and orbital bed velocity (U_{sigb}) values were small. Suspended sediment concentration showed a periodicity correlated with tidal state (i.e., highest at slack low water, indicated on two occasions with solid lines). The dashed line with arrow marks the first flooding tide following the application of terrigenous sediment at Site TK, when the terrigenous deposits were most likely to be advected off the plots and measured by the DOBIE-OBS. There was no such signal detected.

TK neap

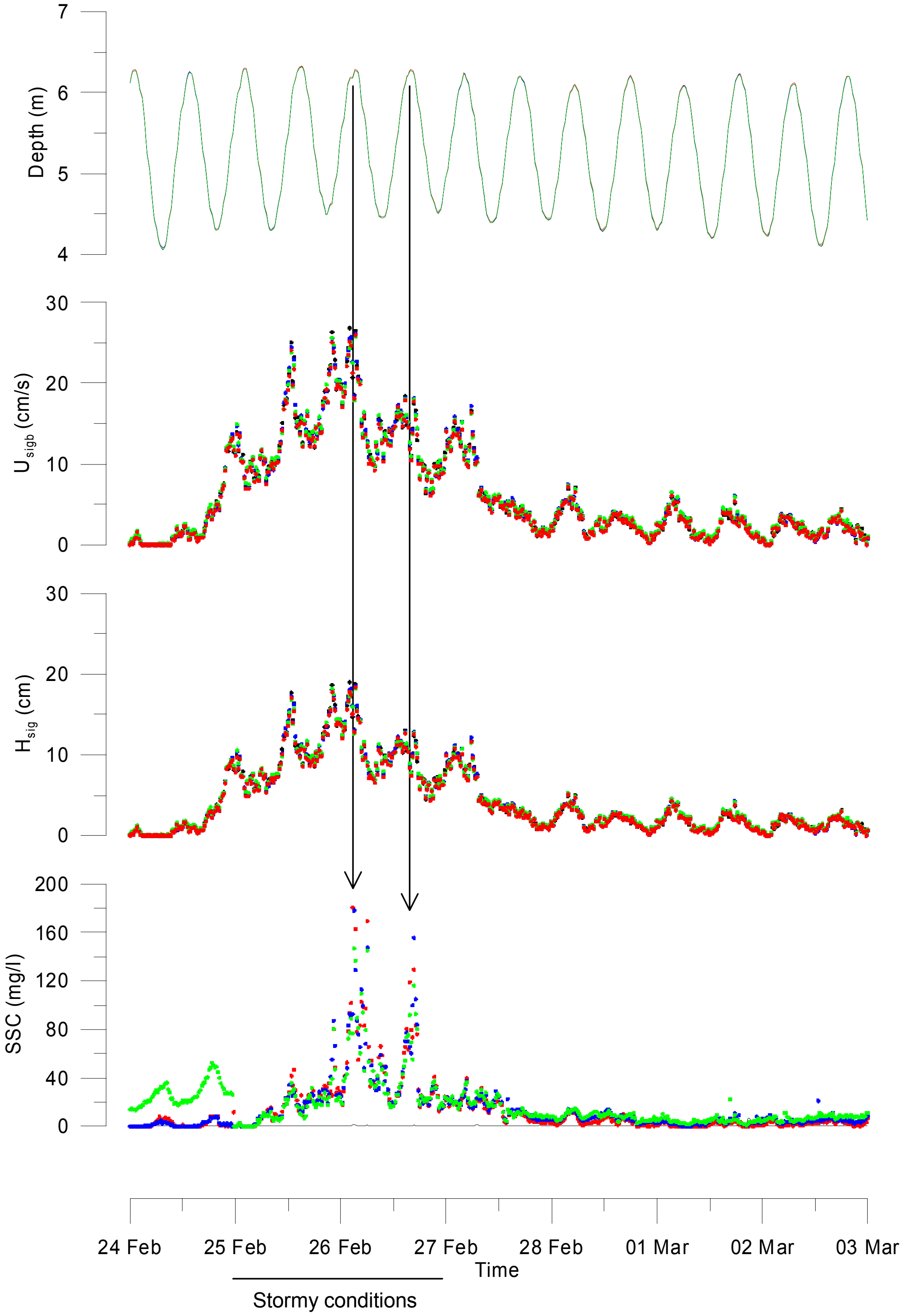


Figure 13: DOBIE-OBS data from Site TK, later in the experimental period. Day 7 at Site TK was 25-February-2003. During the storm, average significant wave height (H_{sig}), orbital bed velocity (U_{sigb}), and suspended sediment concentrations (SSC) all increased markedly. The peaks in each variable were coincident with high tides (see solid lines). Note the change to the axis scale for SSC. Peak values are an order of magnitude higher during the storm at TK than they were the previous week.

3.3 Depth of the terrigenous sediment deposits

To create terrigenous deposits of a desired thickness (i.e., 0 mm, 3 mm, and 7 mm), three distinct experimental treatments were applied at each site (0 litres, 24 litres, and 56 litres of soil-seawater slurry, respectively). To confirm that deposit thickness was related to experimental treatment, and because deposit thickness has proved a valuable explanatory variable in past investigations (Berkenbusch et al. 2001), we measured the thickness of terrigenous sediment in all experimental plots. While relative differences in treatment thickness were captured by all measurement methods, the magnitudes of deposit thickness differed among methods.

Measurements made by divers in situ suggested that relatively thick layers of terrigenous material (several cm) rested atop the plots. The deposits did not appear to fully de-water and compact in the subtidal environment. However, it was difficult for the divers to find a delineated horizon separating a terrigenous deposit and the soft marine sediment layer underneath. The sticky terrigenous material was also transported downward by any probe, ruler, or core pushed through the deposit.

The small sediment cores revealed depositional layers just a few mm deep (Table 1). The measurements obtained from the small cores may be more comparable to those of de-watered terrigenous sediment in previous intertidal deposition experiments; the core samples were assessed in air, and the coring process itself collapses the interstices between sediment particles, forcing pore water out. The thickness of the deposit as assessed from small sediment cores tended to decrease over time. By Day 30, the deposit measurements were approximately 50% as thick or less (Table 1).

Table 1: Depth of terrigenous sediment deposits as assessed from small cores of sediment (2.4 cm diameter). Data are means + 1 *SE*; *n* = 4, which is 1 core per treated plot. Controls never had any measurable terrigenous sediment. No cores were collected at TK on Day 7.

	Site	Thinner treatment	Thicker treatment	Site	Thinner treatment	Thicker treatment
Day 3	MI	2.0 + 0.4	4.0 + 1.1	TK	1.8 + 1.1	3.5 + 0.5
Day 7	MI	2.0 + 1.4	4.0 + 1.4	TK	.	.
Day 14	MI	0.5 + 0. 3	3.0 + 0.4	TK	0.3 + 0.3	1.3 + .9
Day 30	MI	1.0 + 0.6	1.3 + 0.5	TK	0.3 + 0.3	0.8 + 0.8

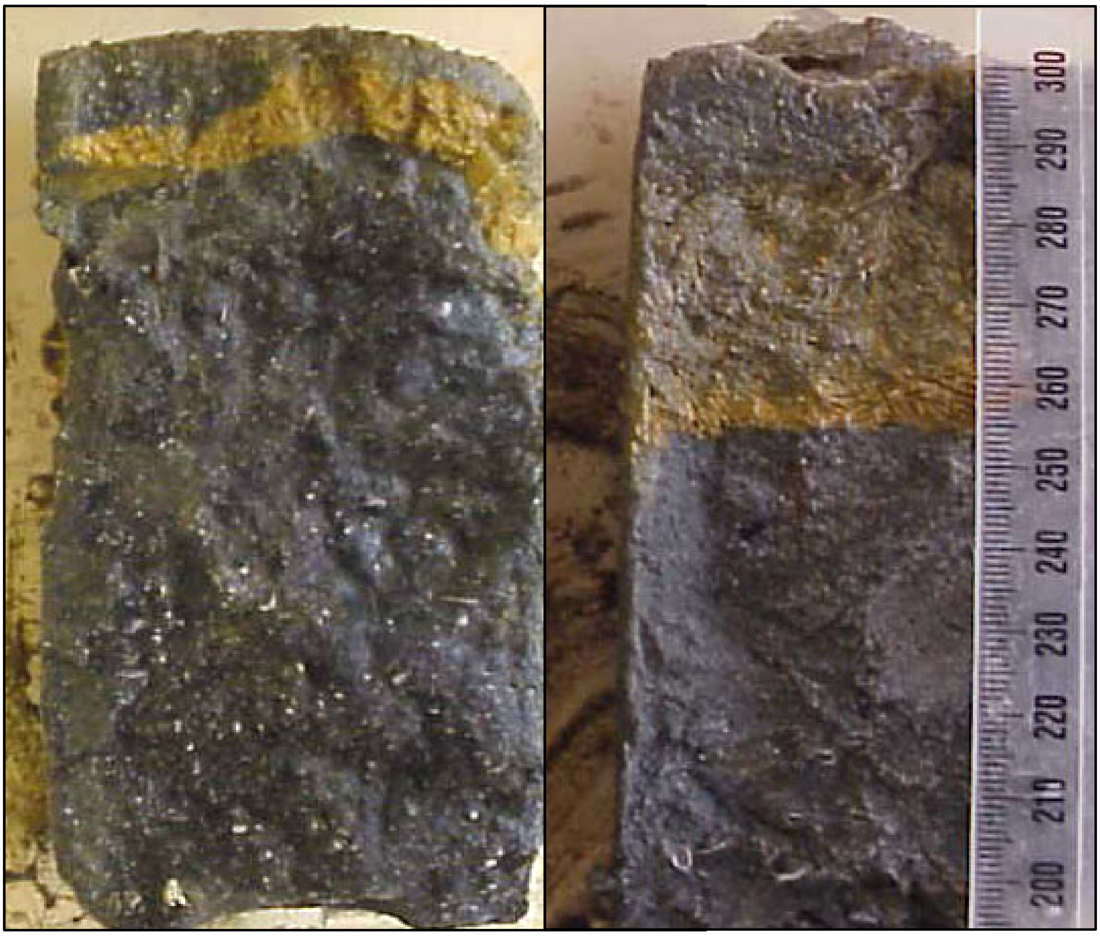
While a substantial amount of terrigenous material persisted until Day 30 in every experimental plot, data from cores of both sizes indicated that TK had less terrigenous sediment than MI by the end of the experiment (see Tables 1 and 2). Furthermore, relative to MI, the deposits at TK were covered by more ambient marine silt on Day 30 (Table 3), meaning that the terrigenous material at TK was deeper in the sediment column. The depositional layers were relatively well defined at MI, whereas the material was more mixed in with marine sediments at TK (Picture 13).

Table 2: Depth of terrigenous sediment deposits as assessed from frozen cores of sediment (5 cm diameter). Data are means + 1 *SE*; *n* = 4, which is 1 core per treated plot.

	Site	Thinner treatment	Thicker treatment	Site	Thinner treatment	Thicker treatment
Day 30	MI	8.5 + 1.9	17.3 + 3.3	TK	2.5 + 1.0	9.8 + 3.9

Table 3: Depth of silt atop terrigenous deposits, as assessed from frozen cores of sediment (5 cm diameter). Data are means + 1 *SE*; *n* = 4, which is 1 core per treated plot.

	Site	Thinner treatment	Thicker treatment	Site	Thinner treatment	Thicker treatment
Day 30	MI	8.9 + 1.4	2.5 + 1.1	TK	14.4 + 4.0	8.4 + 1.9



Picture 13: Sediment cores (5 cm diameter, 12 cm deep) collected from Site MI (left) and Site TK (right) on the final day of the experiment (Day 30). The cores were frozen and then split in order to measure the thickness of the terrigenous deposit we applied. The depth of the marine silt layer resting on top of the plots was also measured, and information about the relative amount of mixing in the sediments was apparent. The ruler to the right shows the scale of the photograph (mm).

3.4 Sediment characteristics

Sediment organic matter content. It was difficult to draw any general conclusions from the sediment organic matter content data, as all main effects and first-order interaction terms were significant at =0.05 (ANOVA, n_{total} = 160, $P < 0.05$ for Treatment, Site, Day, Treatment*Site, Treatment*Day, Site*Day). However, plots treated with terrigenous sediment tended to have higher organic matter content (percent loss on ignition) than control plots, especially at Site MI (Fig. 14). At TK, treated plots had higher ranking sediment organic matter values on four of the five sampling dates, with Day 7 being the only exception (Fig. 14). We conclude that the terrigenous sediment applied (with 4.6% loss on ignition) was slightly richer in organic matter relative to the ambient marine sediments at each site.

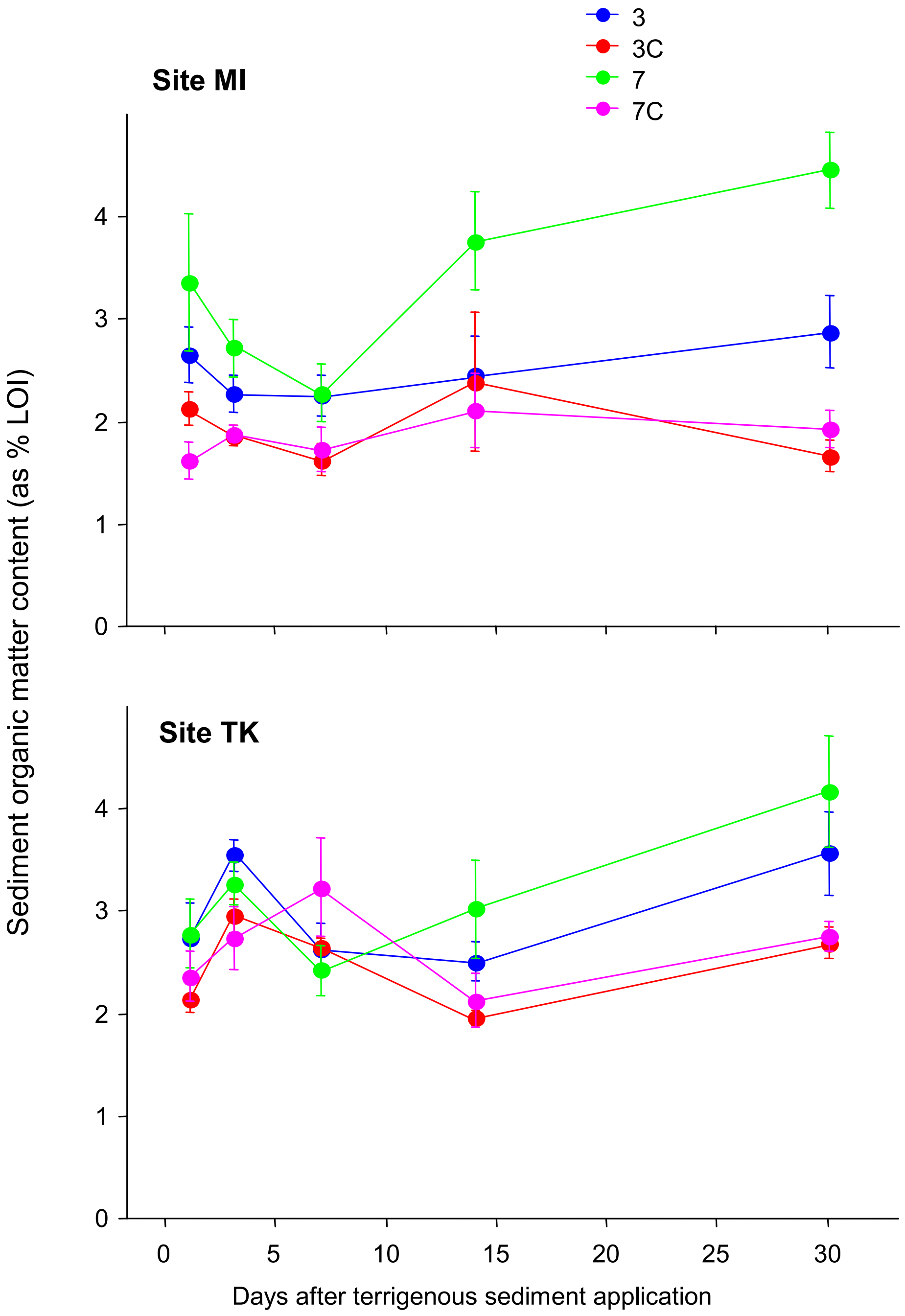


Figure 14: Sediment organic matter content (measured as % loss on ignition). Mean values for each treatment (± 1 *SE*, *n* = 4) are given for each date at each site. Sediments from treated plots (green and blue lines) tended to have a greater content of organic matter.

Sediment grain size. Site MI had coarser sediments than Site TK. As a percentage by weight, control plots at MI were dominated by sands; coarse sands, fine sands, and medium sands were the top three ranking particle size class categories at this site. In contrast, the sediments at Site TK were dominated by smaller particles, namely very fine sands, fine sands, and coarse silt (ranks 1-3).

The terrigenous sediment slurry that we applied was muddy, as >77% of the particles were smaller than 63 m (i.e., silts and clay). Clay particles <3.9 m comprised 9% of the material, and 15-32 m medium silt was the most common particle size category at 20%.

The application of this terrigenous material altered the sediment particle size distributions at each site. Figure 15 shows the proportion of particles in 3 broad particle size categories. At both sites, the grain size distributions in treated plots were skewed towards finer particles, relative to controls. The downward shift in particle size distribution toward the muddy end of the spectrum was apparent on Day 1, just after the application of terrigenous material, and at the conclusion of the experiment as well (i.e., Day 30; Fig. 16).

Although the effect of the terrigenous deposits on grain size was apparent at both sites, the particle size distributions shifted by a larger amount at Site MI (Figs. 15 and 16). For example, while control plots at MI were dominated by sands, plots that received 7 mm of terrigenous sediment were dominated by mud. The top ranking particle size category (of the 11 quantified) was shifted downwards in MI's 3 mm plots as well. At Site TK, in contrast, neither the addition of 3 nor 7 mm of terrigenous material altered the top 3 particle size categories; the proportions changed slightly, but rankings remained the same.

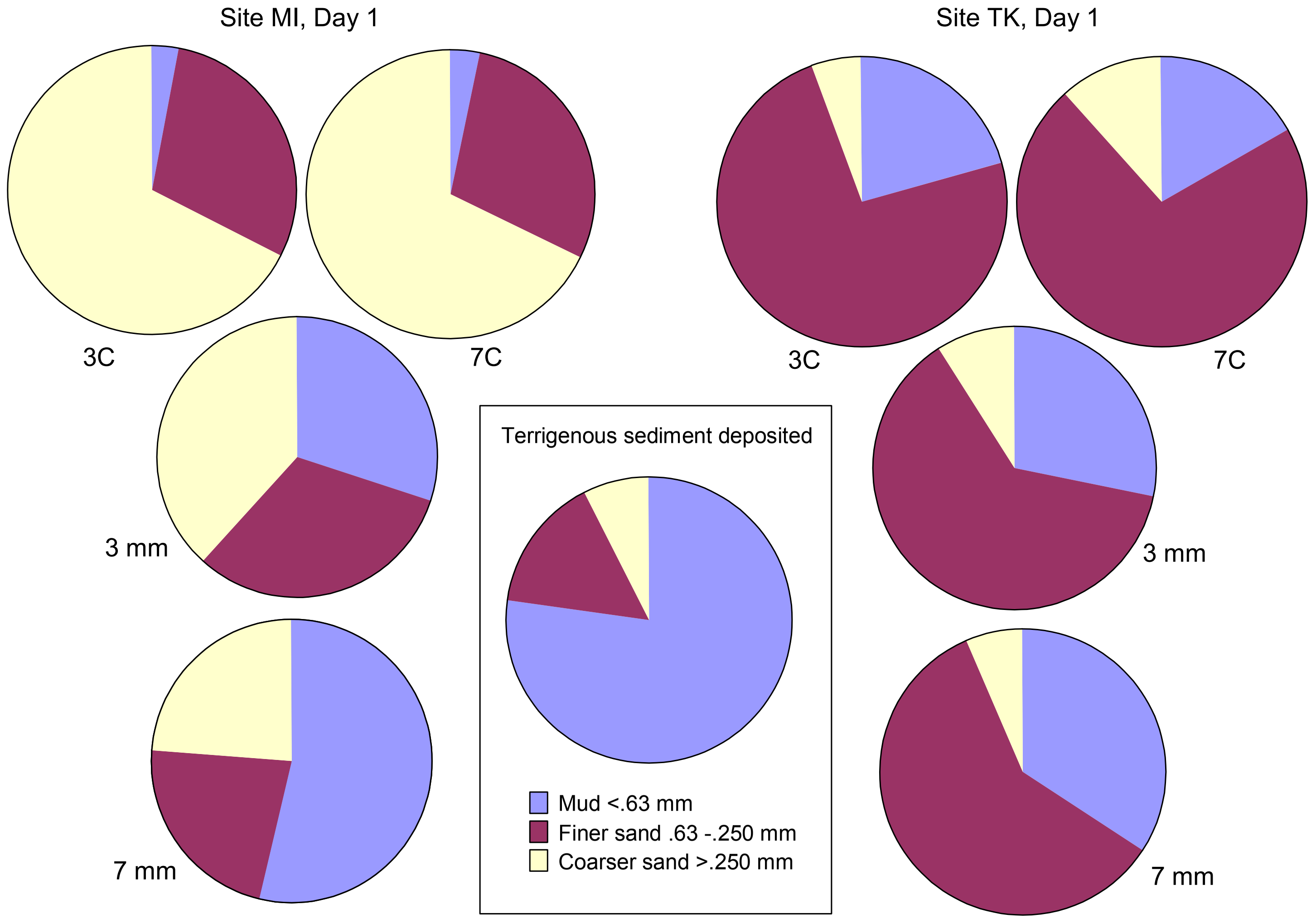


Figure 15: Sediment particle size distribution on Day 1, immediately following terrigenous sediment deposition, in the four experimental treatments at each site. The eleven particle size categories quantified were combined into 3 broad groupings for clarity. Each pie-diagram represents the average of four replicates.

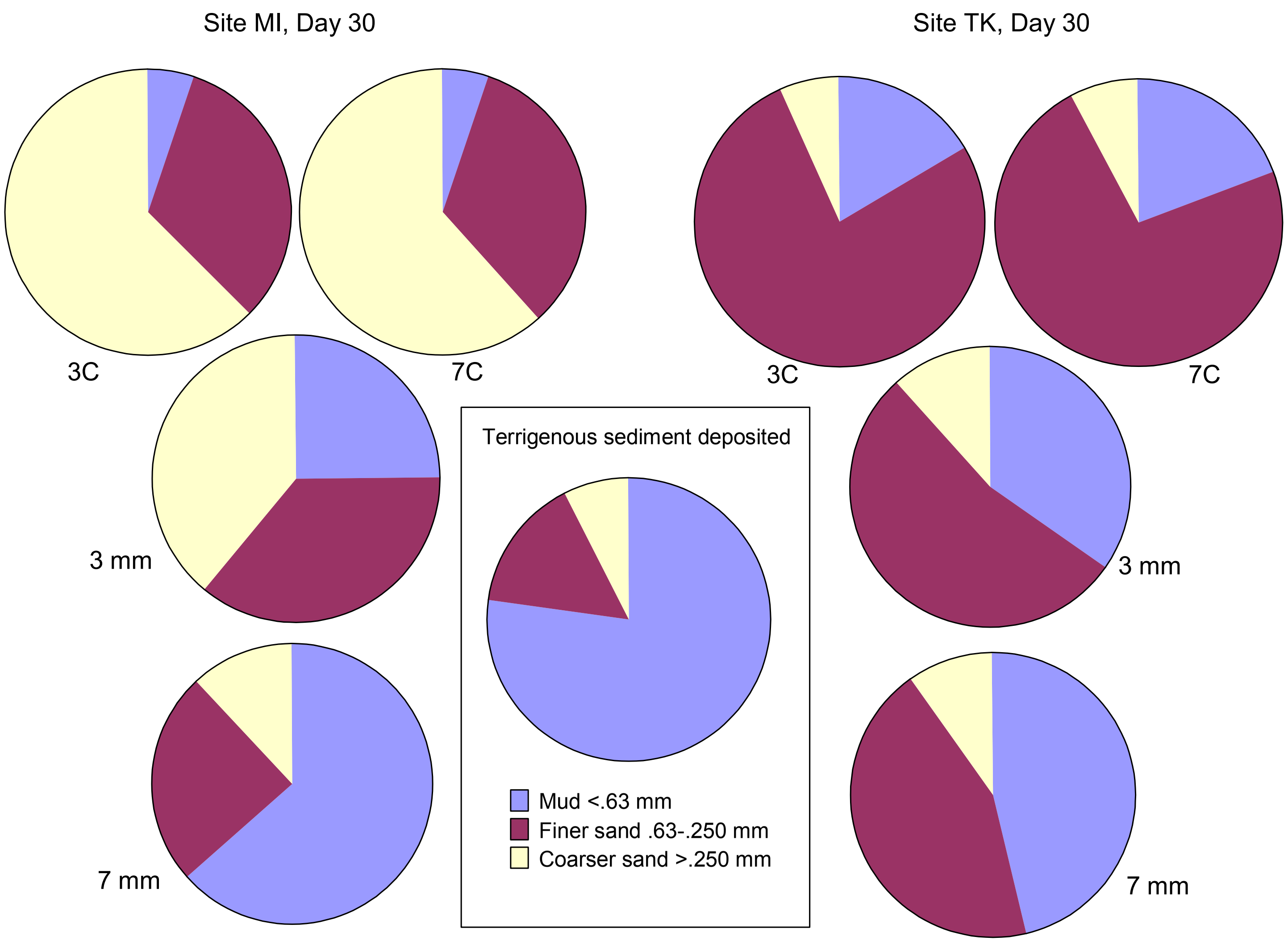


Figure 16: Sediment particle size distribution on Day 30, in the four experimental treatments at each site. Legend same as previous. The eleven particle size categories quantified were combined into 3 broad groupings for clarity. Each pie-diagram represents the average of four replicates.

3.5 Response of Macrofauna

Analysis of similarities (ANOSIM) revealed that macrofaunal community structure differed significantly by site ($P = 0.001$), with an average dissimilarity between sites of 88.74% (Fig. 17). Site MI contained more individuals and more taxa per sample and was significantly more diverse (Table 4). Site MI was dominated mainly by polychaetes, with four polychaete species ranked 5th or higher on each sample date (Table 5). At Site TK, bivalves were dominant, with 3 bivalve species ranked 4th or higher on each sample date (Table 6).

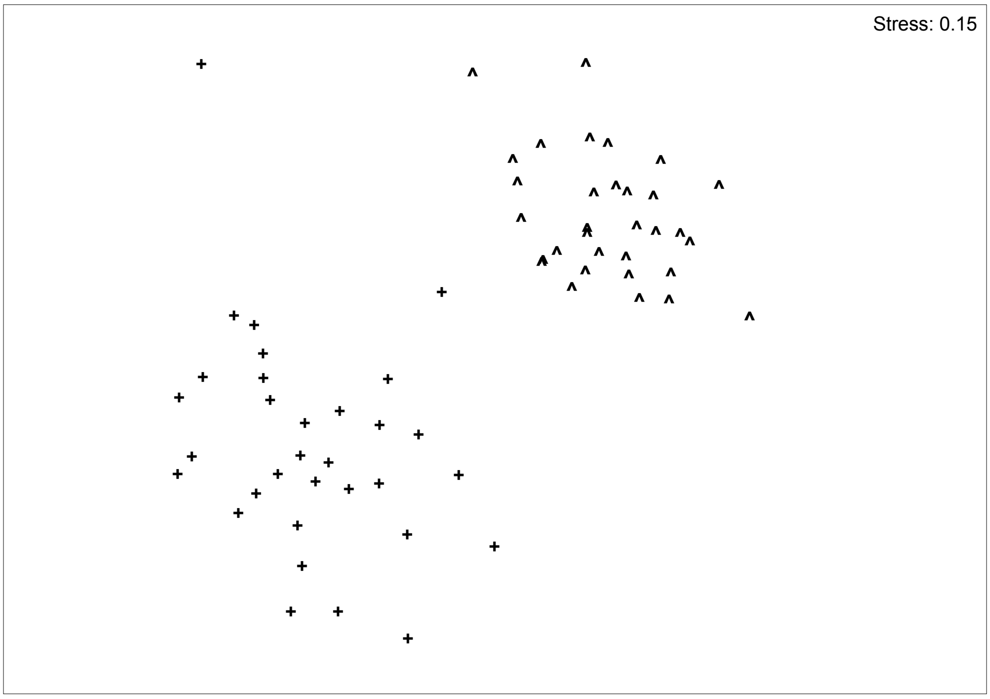


Figure 17: MDS ordination plot of all macrofaunal samples (both dates, both sites, all treatments). Plus (+) indicates Site MI, carrot (^) indicates Site TK. As a non-metric ordination, the plot has no axis labels or units. The two separate clusters indicate differences in macrofaunal community structure with respect to site.

Table 4: Analysis of variance results for three community variables: number of individuals (log transformed to achieve normality and homogeneity of variance), number of taxa, and the Shannon-Wiener diversity index *H'*. Some variables differed significantly with experimental treatment type, day of sampling, and/or site location. Degrees of freedom (DF), Type III sums of squares (Type III SS), mean squares, *F*-values, and *P*-values (Pr > *F*) for all main effects and interaction terms are given. Bold face type indicates statistical significance of $P < 0.05$.

Source of Variation	**DF**	**Type III SS**	**Mean Square**	***F* Value**	**Pr > *F***
(a) log No. Individuals					
Treatment	3	9.04	3.01	11.83	**<0.0001**
Day	1	0.39	0.39	1.53	0.2226
Site	1	17.72	17.72	69.58	**<0.0001**
Day*Treatment	3	0.03	0.01	0.04	0.9873
Site*Treatment	3	1.32	0.44	1.72	0.1745
Day*Site	1	0.60	0.60	2.34	0.1324
Day*Site*Treatment	3	0.37	0.12	0.48	0.6954
(b) No. Taxa					
Treatment	3	445.92	148.64	7.60	**0.0003**
Day	1	102.52	102.52	5.24	**0.0265**
Site	1	1590.02	1590.02	81.30	**<0.0001**
Day*Treatment	3	2.67	0.89	0.05	0.9869
Site*Treatment	3	279.92	93.31	4.77	**0.0055**
Day*Site	1	28.89	28.89	1.48	0.2302
Day*Site*Treatment	3	25.05	8.35	0.43	0.7346
(c) Diversity index *H'*					
Treatment	3	0.32	0.11	1.61	0.1983
Day	1	0.03	0.03	0.49	0.4881
Site	1	1.07	1.07	16.01	**0.0002**
Day*Treatment	3	0.14	0.05	0.70	0.5582
Site*Treatment	3	0.49	0.16	2.45	0.0746
Day*Site	1	0.01	0.01	0.10	0.7556
Day*Site*Treatment	3	0.11	0.04	0.54	0.6579

Table 5: Macrofauna in control cores at Site MI on Days 7 and 30. All data are presented as mean number per core + 1 *SE*, *n =* 8 control cores per site per date. Taxa are listed according to abundance ranking; Taxa with an average of <1 individual per core are not listed. Letters in parentheses indicate the type of organism (B=bivalve mollusc, A=amphipod crustacean, C=cumacean shrimp, P=polychaete worm).

Rank	**Day 7**	**Mean + *SE***	**Rank**	**Day 30**	**Mean + *SE***
	Individuals	119.5 + 19.0		Individuals	166.6 + 38.2
	Taxa	23.9 + 1.5		Taxa	28.4 + 2.1
1	Exogonid (P)	32.0 + 9.4	1	Exogonid (P)	57.4 + 20.5
2	Maldanid, *Asychis* (P)	17.8 + 6.4	2	Maldanid, *Asychis* (P)	16.0 + 3.7
3	Chaetopterid (P)	10.3 + 6.4	3	Polydorid spp. (P)	8.4 + 2.5
4	*Heteromastus* (P)	5.8 + 1.0	3	Ostracoda	8.4 + 3.3
5	Phoxocephalidae (A)	4.9 + 1.1	5	Sabellid (P)	7.9 + 4.5
6	Tanaidacea	4.1 + 1.3	6	*Heteromastus*	7.5 + 0.9
7	*Euchone* (P)	3.9 + 1.5	7	Maldanid sp. (P)	7.3 + 2.9
8	*Gynodistylis* (C)	3.1 + 3.1	8	Tanaidacea	6.0 + 2.2
8	*Scoloplos* (P)	3.1 + 1.1	9	Chaetopterid (P)	3.6 + 1.6
10	Ostracoda	2.6 + 1.5	10	*Scoloplos* (P)	2.8 + 1.0
11	Oligochaeta	2.1 + 0.9	11	Phoxocephalidae (A)	2.5 + 1.0
12	Polydorid spp. (P)	2.0 + 1.1	12	*Euchone* (P)	2.3 + 1.3
13	Paraonid (P)	1.5 + 0.8	12	Cirratulid (P)	2.3 + 0.6
14	*Nucula hartvigiana* (B)	0.8 + 0.4	14	Paraonid (P)	1.5 + 0.6

Table 6: Macrofauna in control cores at Site TK on Days 7 and 30. All data are presented as mean number per core + 1 *SE* (*n* = 8 control cores per site per date). Taxa are listed according to abundance ranking; Taxa with an average of <1 individual per core are not listed. Letters in parentheses indicate the type of organism (B=bivalve mollusc, A=amphipod crustacean, C=cumacean shrimp, P=polychaete worm).

Rank	TK Day 7	Mean + *SE*	Rank	TK Day 30	Mean + *SE*
	Individuals	34.9 + 3.8		Individuals	33.5 + 2.2
	Taxa	11.6 + 0.9		Taxa	12.9 + 0.9
1	*Theora lubrica* (B)	8.3 + 0.8	1	*Theora lubrica* (B)	9.8 + 1.4
2	Ostracoda	7.5 + 1.3	2	Ostracoda	5.6 + 2.1
3	*Athritica bifurca* (B)	2.5 + 1.3	3	*Athritica bifurca* (B)	2.8 + 1.1
3	*Nucula hartvigiana* (B)	2.5 + 0.6	4	*Nucula hartvigiana* (B)	2.3 + 0.6
5	Phoxocephalidae (A)	2.4+ 0.7	5	Cirratulid (P)	2.1+ 0.6
6	Oligochaeta	2.0 + 1.2	6	Paraonid (P)	1.1 + 0.4
7	*Hemileucon* (C)	1.9 + 0.7	7	Phoxocephalidae (A)	1.0 + 0.3
8	Paraonid (P)	1.4 + 0.5	7	Oligochaeta	1.0 + 0.3
9	Cirratulid (P)	0.9 + 0.4	7	*Hemileucon* (C)	1.0 + 0.3

Differences between sites (which were obvious and expected a priori) generated the largest amount of variation in the macrobenthic community structure (Fig. 17), and this limited our ability to determine the effects of the terrigenous sediment treatments. Therefore, all analyses described hereafter were performed on data from each site separately.

At Site MI, small polydorid, maldanid, and sabellid polychaetes were common on Day 30 (Table 5), apparently recruiting sometime between our two sampling dates, and effects of sampling date on macrobenthic community structure were nearly significant in the 2-way crossed NP-MANOVA analysis (P=0.0698). However, this should not be interpreted as recovery, since differences among the experimental treatments persisted across days (P=0.0268) while day *treatment interaction terms were not significant (P=0.9980). The terrigenous material in treated plots may have deterred recruits, as the maldanids and sabellids only recruited to control areas (maldanids averaged about 7 individuals per control, sabellids averaged between 4 and 12 individuals per control, and both species were absent from all 3 and 7 mm plots).

Ordination plots (MDS) of treatment means demonstrate the changes to macrobenthic community structure driven by depositional thickness. At Site MI (Fig. 18), both types of treated plots were separated from controls, and this trend was similar on both days. The relative distance between controls and 7 mm plots was greater than the distance between controls and 3 mm plots, suggesting increased change in macrofaunal community composition with increasing depositional thickness. While the 3 and 7 mm treatments were both separated from controls, only the 7 mm treatment differed significantly (a posteriori tests following NP-MANOVA, *P*=0.2452 for 3C vs. 3, *P* =0.0132 for 7C vs. 7).

Similarly, at Site TK, the effect of treatment was significant (*P*=0.0088), and there were no significant differences in macrobenthic community structure between Days 7 and 30 (*P*=0.2438) and no significant day*treatment interactions (*P*=0.6304). Here, however, there was little apparent effect in the 3 mm plots (*P*=0.6346) relative to the strong and significant effects in the 7 mm plots (*P*<0.0068). A comparison of Figures 18 and 19 shows the relatively greater sensitivity of the MI communities to terrigenous sediment deposition, particularly at the 3 mm level. Perhaps high turbidity and bedload sediment movement rates at TK have conditioned the animals to cope with low-level disturbances. Deposits beyond a certain threshold thickness may still be deleterious, and this was apparently the case for 7 mm deposits at both sites.

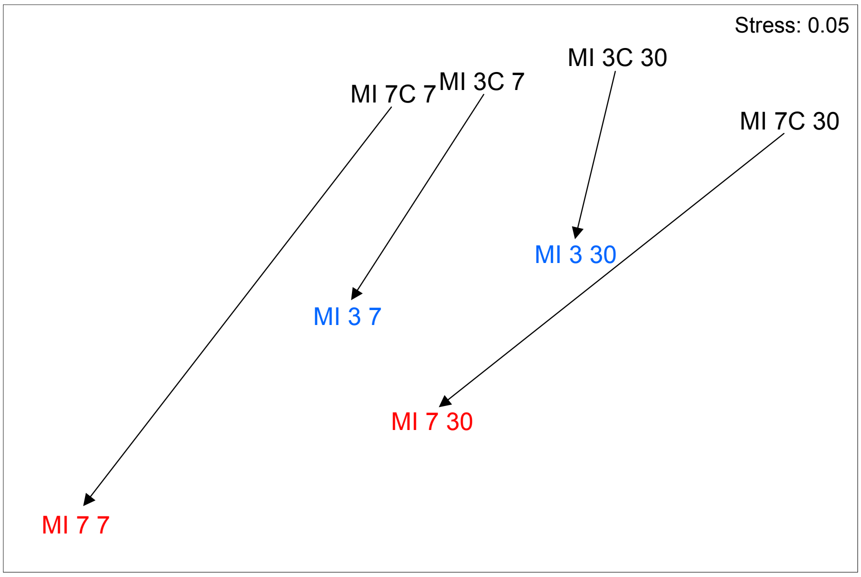


Figure 18: MDS ordination plot of macrofaunal community data at Site MI. Treatment means are displayed for each treatment on Days 7 and 30. Blue print = 3 mm treatment; red print = 7 mm treatment. Arrows indicate the relative distance between treatment and control plots on each date. The greater the distance in ordination space, the greater the community dissimilarity.

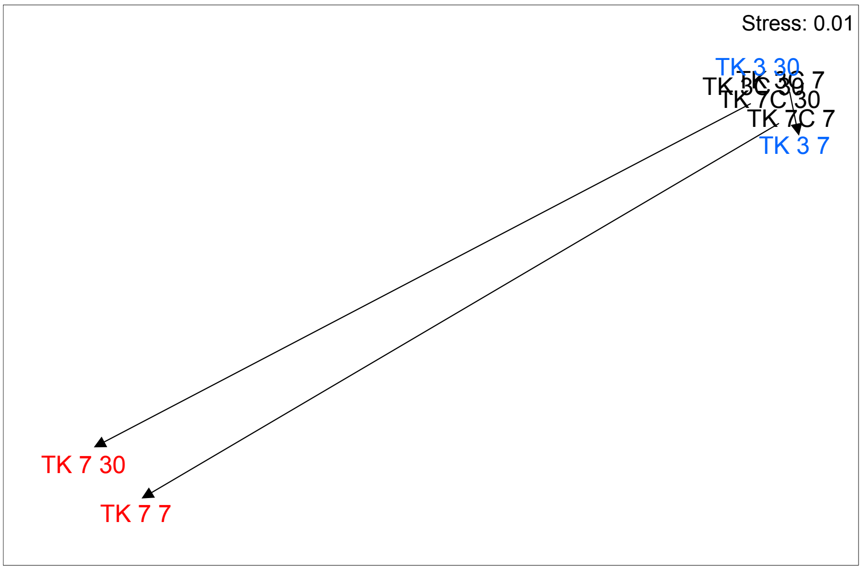


Figure 19: MDS ordination plot of macrofaunal community data at Site TK. Treatment means are displayed for each treatment on Days 7 and 30. Blue print = 3 mm treatment; red print = 7 mm treatment. Arrows indicate the relative distance between treatment and control plots on each date. Notice that communities in 3 mm plots at TK are not much different from those in controls.

Statistical analyses of the number of individuals, number of taxa, and the densities of several abundant species at each site revealed treatment effects. Figures 20 and 21 show data from every date, site, and treatment combination. Recall, however, that our analysis was performed after calculating the difference in abundance for every treatment-control pair (i.e., 3C minus 3, and 7C minus 7), as our design allowed. Given that the community variables (number of individuals, number of taxa) and the multivariate analyses of community structure showed no indications of recovery (i.e., no treatment *day interactions), we pooled data across dates for our individual species analyses for greater statistical power and clarity.

Figures 22, 23, and 24 show these treatment-control differences. At Site MI, numbers of individuals and taxa (Fig. 22) and the densities of five common polychaete and crustacean groups (Fig. 23) were all significantly reduced by the 7 mm terrestrial sediment treatments. The response to the 3 mm treatments was weaker but still significant for *Asychis*, *Heteromastus*, and the total number of individuals and taxa. At Site TK, the 3 mm treatment did not reduce the number of individuals or taxa or any of five common bivalve and crustacean groups, again signalling the relative tolerance of the TK community to this amount of terrigenous material. The thicker 7 mm treatments at TK did reduce the densities of these variables, though the response was not as strong as it was at Site MI (several *P*-values were marginally significant; Fig. 24).

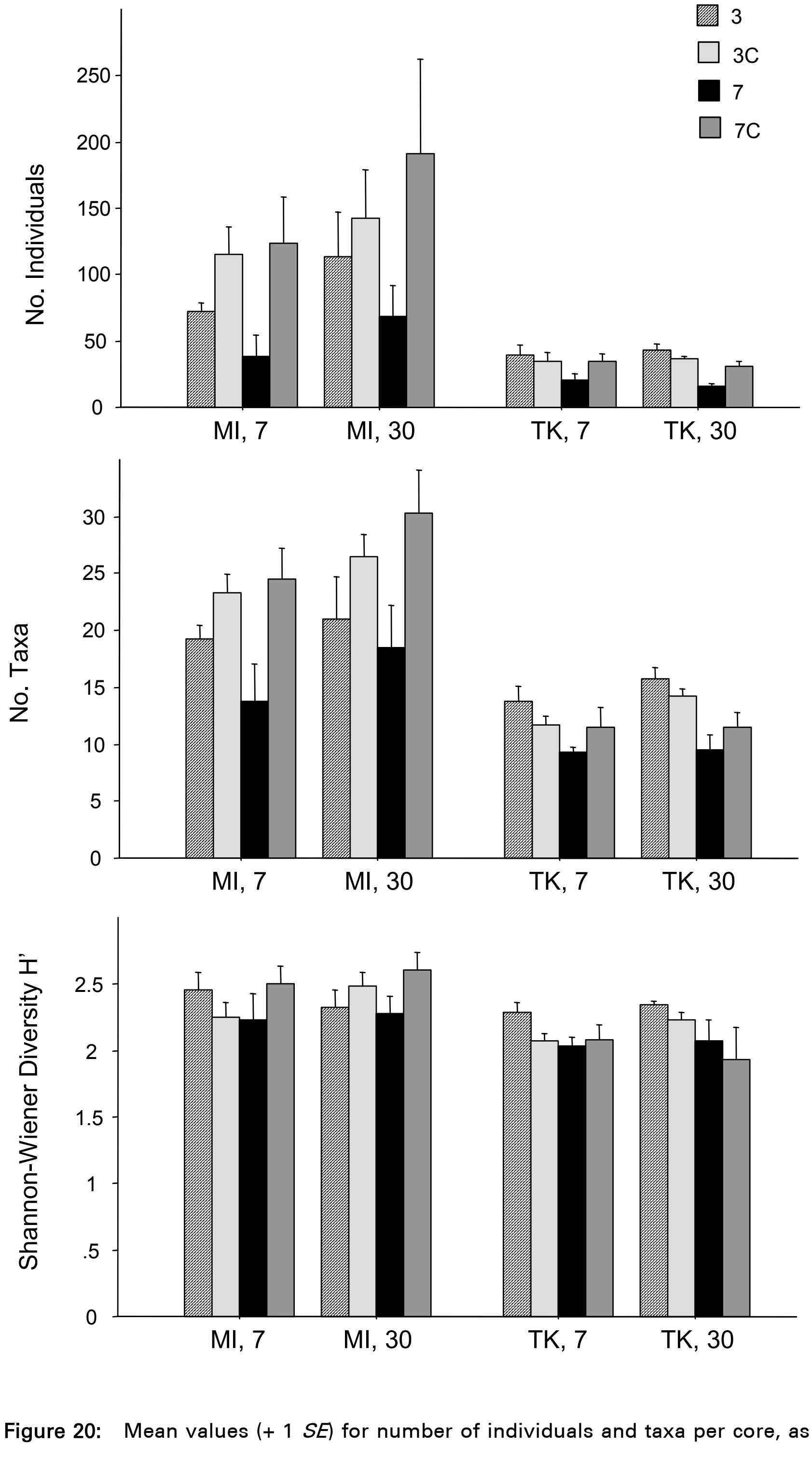


Figure 20: Mean values (+ 1 *SE*) for number of individuals and taxa per core, as well as Shannon-Wiener sample diversity. $n = 4$ replicates treatment^{-1} site^{-1} date^{-1}. *X*-axis lists site (MI or TK) and sampling date (7 or 30).

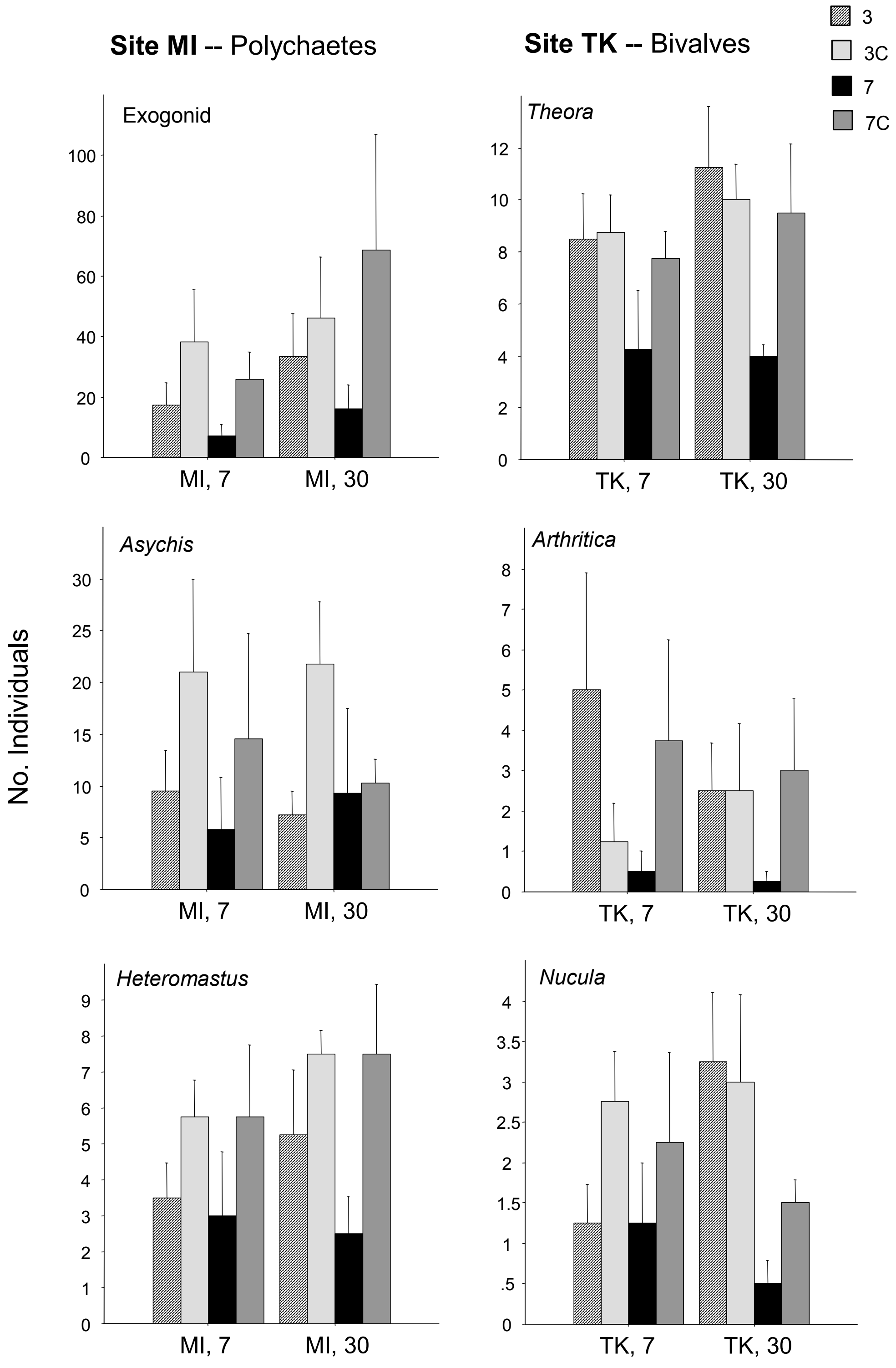
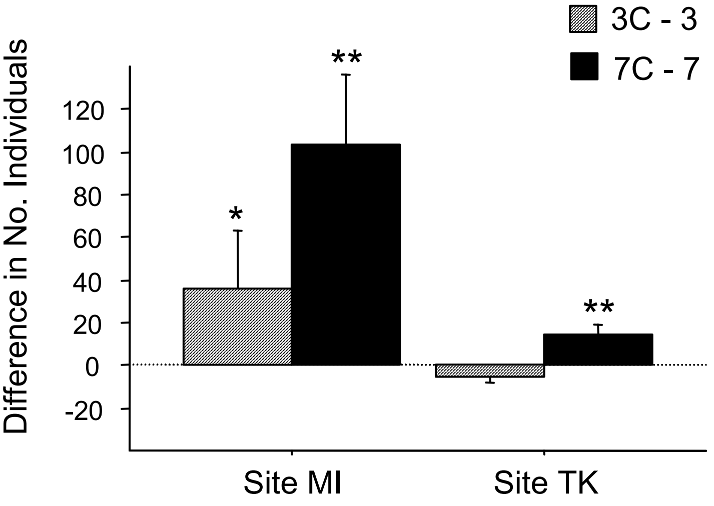


Figure 21: Mean number of individuals (+ 1 *SE*) of common taxa from each site. $n = 4$ replicates treatment^{-1} site^{-1} date^{-1}. *X*-axis lists site (MI or TK) and sampling date (7 or 30).



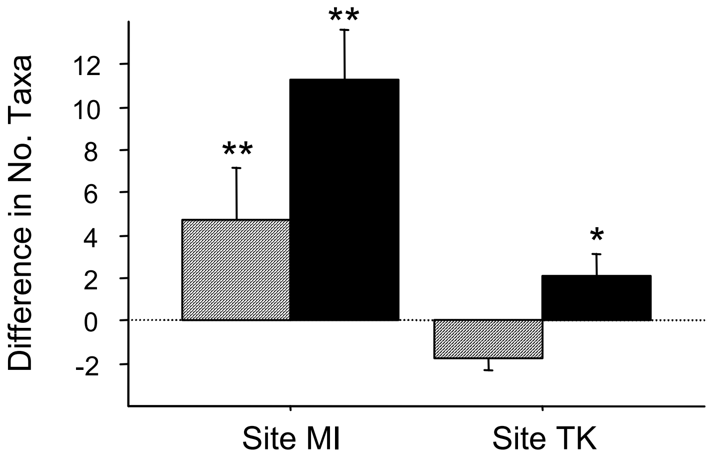


Figure 22: Mean difference in the number of individuals and taxa (+ 1 *SE*) between treatment and control pairs. Data from Days 7 and 30 have been pooled (see p. 52), thus $n = 8$ per average. A difference of zero indicates relative similarity between treatment and control data. Greater mean values (bar heights in the positive direction) indicate greater negative impact. These impacts are given for 3 mm and 7 mm treatments (black stripes and black solids, respectively). Results of Wilcoxon two-sample tests on the data pairs are given as asterisks and denote differences significantly greater than zero. A single asterisk is marginally significant ($P < 0.10$) and double asterisks are significant at $P < 0.05$.

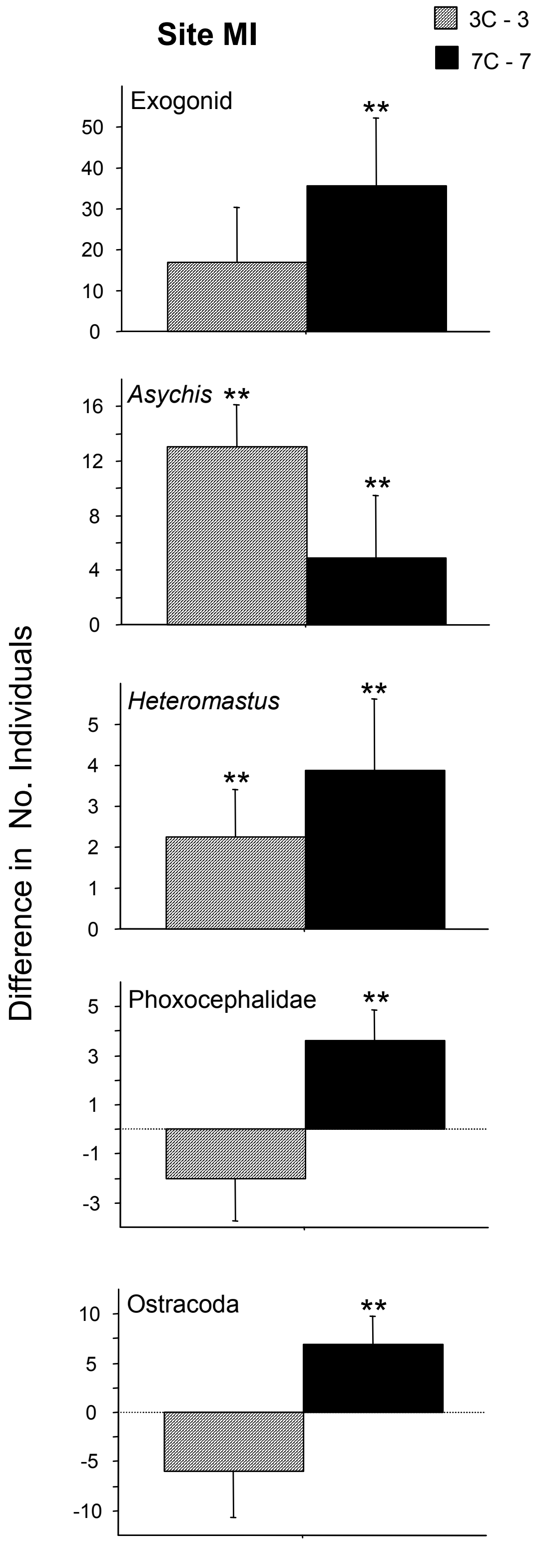


Figure 23: Mean difference in the common taxa at Site MI (+ 1 *SE*) between treatment and control pairs. Data from Days 7 and 30 have been pooled (see p. 52), thus *n* = 8 per average. Details of this figure are otherwise similar to those of Fig. 22.

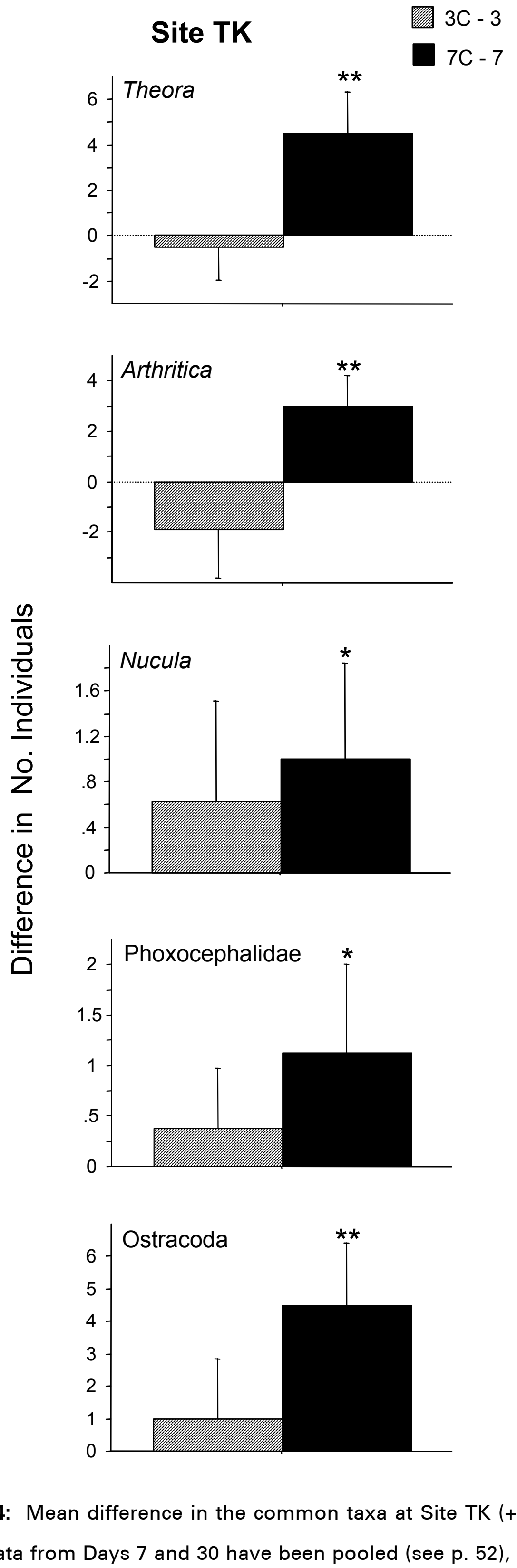


Figure 24: Mean difference in the common taxa at Site TK (+ 1 *SE*) between treatment and control pairs. Data from Days 7 and 30 have been pooled (see p. 52), thus *n* = 8 per average. Details of this figure are otherwise similar to those of Fig. 22.

3.6 Suspension Feeding Results

Condition.

Across the 3 genera (Atrina, Aaptos, Styela), all animals exhibited highest condition in the control plots, indicating that terrigenous material affects them negatively.

Condition of Atrina was significantly greater in controls than it was in the 7 mm treatments at both sites (top panel, Fig. 25). However, at Site MI, the 3 mm treatments were also significantly different from the controls, suggesting that smaller amounts of sediment deposition will affect the condition of Atrina at this site.

The condition of Aaptos collected from Site MI was significantly greater in the control plots than it was in the 3 and 7 mm treatments (top panel, Fig. 26). The condition of control sponges from Site MI did not differ significantly from the condition of sponges at Iris Shoal, indicating that the transplantation of sponges did not harm these animals.

Because the condition of Styela was measured in aggregate, rather than on individuals, the significance of differences between treatments and sites could not be tested. However, the condition of animals collected from within our experimental sediment deposits was less than half the level measured for control animals at both sites (Fig. 27). Comparing controls, the condition of Styela was similar at both sites.

Oxygen consumption, nitrogen excretion and oxygen to nitrogen ratios.

Atrina from controls at Sites MI and TK had higher oxygen consumption than those in the sediment treatments. The *Aaptos* from control plots at MI also had higher oxygen consumption than the sponges exposed to sediment. For nitrogen excretion rates and nitrogen ratio calculations, there were few consistent differences between genera and no significant effects of sediment deposition were detected.

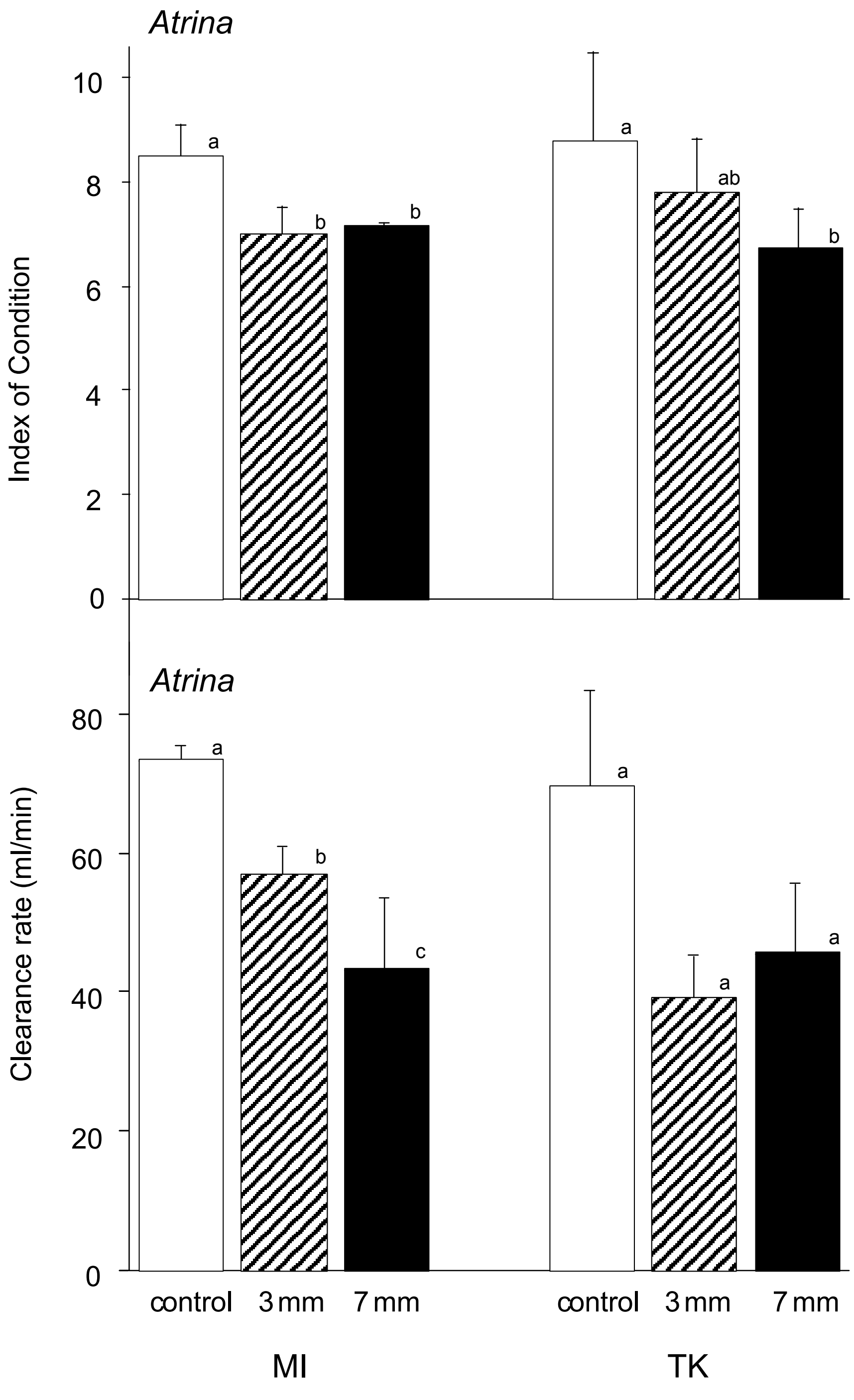


Figure 25: Weight-corrected index of condition (top panel) and clearance rate (bottom panel) of native horse mussels, *Atrina zelandica*, at Sites MI and TK. Clearance rate is defined as the volume of water cleared by an animal per unit time. The mussels had been exposed to the sediment treatments (indicated on the *X*-axis) for 22 days in situ before these measurements were made. Data are means + 1 *SE*. Letters atop bars indicate results of post-hoc tests; means that share letters are not significantly different from each other.

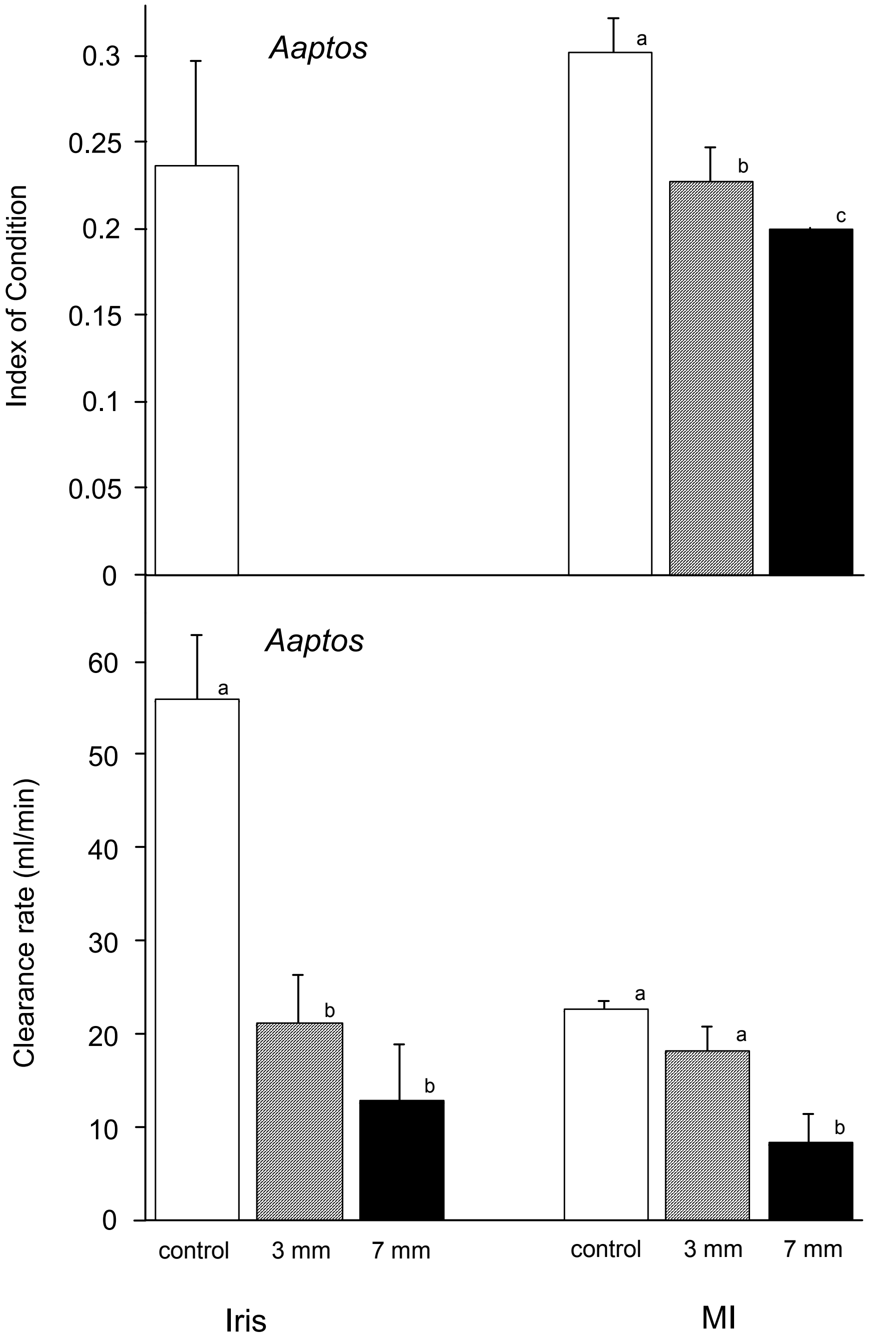


Figure 26: Size-corrected index of condition (top panel) and clearance rate (bottom panel) of golf-ball sponges, genus *Aaptos*. Clearance rate is defined as the volume of water cleared by an animal per unit time. The sponges at MI were exposed to sediment treatments (indicated on the *X*-axis) for 22 days in situ before these measurements were made. Iris Shoal was the donor site from which the sponges were originally transplanted (i.e., they had not been exposed to terrigenous sediment at all until the laboratory trials commenced). Data are means + 1 *SE*. Letters atop bars indicate results of post-hoc tests; means that share letters are not significantly different from each other.

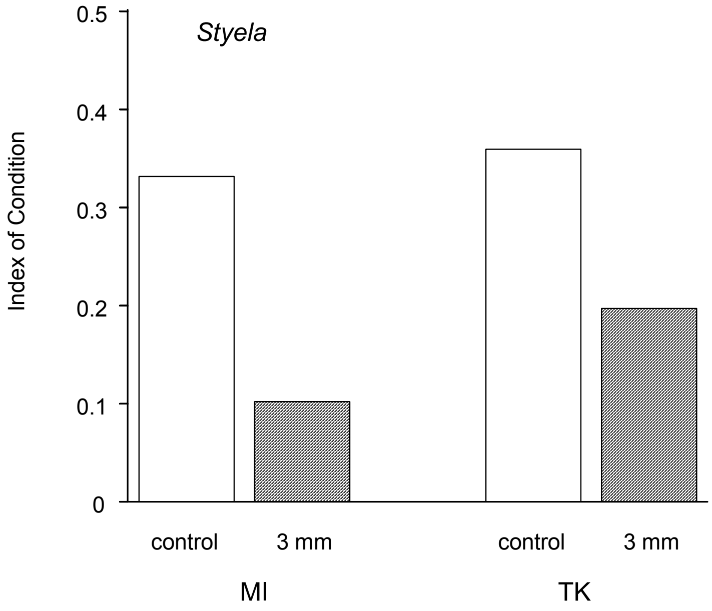


Figure 27: Condition of the solitary ascidian *Styela plicata* at the two experimental sites, MI and TK. Animals were measured in aggregate, thus data are means without error estimates.

Feeding rates

Feeding rates of both *Atrina* and *Aaptos* were significantly affected by the sediment deposition. The decrease in condition of sediment-treated animals (over three weeks) was apparently related to their feeding capabilities. Both *Atrina* and *Aaptos*, when placed in raw seawater (no sediments added), were unable to feed efficiently, as demonstrated by the bottom panels of Figures 25 and 26.

Atrina from control plots at MI cleared greater volumes of water than *Atrina* from either of the treated plots at MI. There were also significant differences between animals in the 3 and 7 mm treatments. Such clear differences were not found for the TK animals, however. Here, clearance rates were only significantly different at the $P<0.10$ level for control vs. 3 mm and control vs. 7 mm comparisons.

Similar to *Atrina*, sponges from control plots at Site MI also cleared greater volumes of water than the sponges treated with terrigenous sediment (bottom panel, Fig. 26). Naïve sponges from the donor site at Iris Shoal also exhibited a similar clearance rate response, indicating that effects from terrigenous sediment occur rapidly (within 1 hour) and can last for at least three weeks following a depositional event in the field.

4. DISCUSSION

The terrigenous sediment deposited to subtidal habitats in Mahurangi Harbour and Kawau Bay remained inside the experimental plots for at least one month. While there was some indication of biological activity resuspending the deposits, most of the terrigenous material was buried by the bed load transport of marine sediments. Sediment cores collected on the final day of the experiment (Day 30) revealed layers of terrigenous material underneath the surface of the sediment, and samples of the top 2 cm revealed the influence of terrigenous material on the habitat's sediment particle size distribution; experimental plots at both sites became muddier as a result of the terrigenous sediment we deposited, and they remained muddier and significantly different from controls for the duration of the study.

Similar to previous experiments in intertidal habitats, the application of terrigenous sediment significantly altered macrobenthic community structure and reduced the number of individuals and taxa present at each subtidal site. The magnitude of effects varied between the MI and TK sites with stronger effects at the site in Kawau Bay. The densities of several common species (generally polychaetes at Site MI and bivalves at Site TK) were also affected, more so in the thicker 7 mm plots versus the thinner 3 mm ones. Similar to experiments in Whitford, where a comparable thickness of terrestrial sediment was applied, total densities and densities of individual taxa changed by about 50%. None of the individual taxa assessed showed consistent positive responses to the addition of terrestrial sediment, and overall there was little sign macrobenthic community recovery during the 30-day experiment.

In addition to impacts on small benthic macrofauna, the terrigenous sediment affected larger species with key ecological functions. For example, the terrigenous sediment deposits smothered infaunal burrowing urchins (*Echinocardium australe*). In the laboratory, these urchins will emerge from the sediment when oxygen concentrations are low, and we suspect that the field response was driven by sediment hypoxia/anoxia as the terrigenous sediment blocked oxygen exchange across the sediment water interface. Urchins are large-sized, mobile creatures that can occur at high densities and can move several body lengths per day, and their capacity to mix the sediment and release nutrients from sedimentary pore water is significant (Widdicombe and Austen 1998, Bird et al. 1999). The loss of these animals would likely translate to impaired ecological and ecosystem functioning in estuarine and coastal marine habitats.

Another key species common in Mahurangi Harbour and Kawau Bay is the native horse mussel, *Atrina zelandica*. We did not observed any *Atrina* mortalities as a result of experimental sediment applications. However, several results provided evidence of physiological harm. Most notably, the ratio of tissue weight to shell weight (an index of condition) was significantly lower for *Atrina* exposed to terrigenous mud, and clearance and filtration rates suggested that feeding capacity (and thus potentially their scope for growth) was impaired by terrigenous sediment. This information builds on previous studies that have demonstrated the sensitivity of *Atrina* to gradients of suspended sediment concentrations in Mahurangi harbour (Ellis et al. 2002). *Atrina* are large organisms which affect numerous benthic processes, from near-bed hydrodynamics to sediment biogeochemistry, to water column nutrient regeneration, to macrobenthic biodiversity. Reductions in condition and feeding that translate to lower reproductive fitness would tend to reduce *Atrina* populations over longer time scales, particularly if terrigenous deposition events of the magnitude we simulated are chronic, rather than isolated.

4.1 Site Differences: the health of Mahurangi Harbour

In nearly all analyses, from multivariate assessments of macrofaunal community composition, to the responses of individual taxa, to the effects on dominant suspension feeders, the communities at Site MI (Kawau Bay) appeared to be more sensitive to terrigenous sediment than those at Site TK (Mahurangi Harbour). To generally summarize all results, both the 3 and 7 mm treatments caused significant change at MI, whereas only the more severe 7 mm treatments caused significant change at TK. It is difficult to determine whether the increased tolerance to terrestrial sediment at TK is typical of estuaries in general, or whether the muted response at TK was reflective of a degraded condition at this particular site.

Chronic terrigenous material loading and pulsed depositional events associated with land use change around Mahurangi Harbour may have reduced or eliminated the most sensitive taxa at TK prior to our experimental work, making the present day communities seem more tolerant of such disturbances. If benthic communities at TK have been chronically exposed to terrigenous material, the sediments we sampled as controls may have been degraded, leading to smaller differences between treated and control plots. Thus the implication of tolerance to terrigenous sediments by TK communities may be an artefact of gradual environmental change inside Mahurangi Harbour. Certainly, the monitoring programme conducted in the harbour is indicating broad-scale ecological change consistent with elevated sediment loading (Cummings et al. 2003a).

However, there are reasons why TK might indeed be a more sediment-tolerant site than Site MI, without invoking any arguments of human degradation. Independent of human influences, estuaries are naturally more turbid than open coastal environments. Furthermore, narrow channels and the overall geography of most estuaries equates to significant tidal currents, increasing the chances for sediment resuspension and bedload sediment transport. Finally, with rivers as the source of terrigenous sediment, estuaries receive greater concentrations of it than adjacent habitats offshore. Therefore, estuarine fauna may be more conditioned to cope with sediment movement and sediment deposition than fauna in coastal habitats nearby.

Ambient sediments at TK had greater proportions of mud (<63 µm) than did ambient sediments at MI. As a consequence, the experimental addition of terrigenous sediment (with ¾ of its mass composed of particles < 63 µm) did not alter the sediment particle size distribution as drastically at TK as it did at MI. Thus, even though we added the same amount of terrigenous material to both MI and TK, the magnitude of disturbance (i.e., the amount of change from status quo) was likely greater at MI.

Faunal differences between the TK and MI sites are important in the differential response. For example, polychaetes and small crustaceans numerically dominate the macrofauna at MI, while small bivalves were more abundant at TK. Based on earlier studies and the trends apparent in the Mahurangi monitoring data, we would expect most bivalve species to decrease in density in response to sediment loading. This indicates that site pre-conditioning is not an over riding factor influencing the magnitude of the effects at the two sites. Furthermore, although only the small crustaceans, Phoxocephalidae and Ostracoda, were numerically dominant taxa shared by the two sites, both recorded significantly lower densities in the 7 mm treatments at both sites. While the magnitude of these differences is dependent on density, the treatment effects were proportionally comparable (a 21% to 36% decline in response to the 7 mm treatment).

The amount of disturbance to the large suspension feeding taxa may have also differed between sites. Bottom water at TK was much more naturally turbid than bottom water at MI, as indicated by the four DOBIE-OBSs measuring total suspended sediment loads at each site. For the TK suspension feeders living in an environment with high turbidity, experimental increases in sediment loading may have been proportionately small, relative to the MI animals that were used to clearer water.

Fine sediments covered the plots much more quickly at TK than at MI, probably due to greater water column turbidity and faster current speeds at TK, factors related to sedimentation rates and bedload sediment transport rates, respectively. The marine silt layer atop the terrigenous deposits may have provided small organisms with suitable habitat for recolonisation. Even at MI, tube-building polychaetes (polydorids) were observed in the silt layer atop experimental plots during the later part of the experiment. However, with the silt layer forming more quickly and more deeply at TK, the opportunity for macrofaunal recolonisation was probably enhanced relative to MI. In addition, the greater number of holes and burrows at TK was indicative of greater bioturbation and sediment reworking rates, another factor that may have increased the break-up of the terrigenous sediment layers and reduced the magnitude of the macrofaunal response at this site.

4.2 Comparisons to previous studies: intertidal vs. subtidal experiments

Based on previous work in intertidal environments, we knew that just a few mm of sediment were necessary to influence some intertidal communities, and that thick deposits were clearly catastrophic. The results we obtained in the present study, from subtidal habitats in Mahurangi Harbour and Kawau Bay, were similar to those obtained previously in Whitford's intertidal habitats (Berkenbusch et al. 2001). Again we observed a gradient in response to terrigenous sedimentation; more sediment translated to greater effects. Those effects were manifested as fewer individual macrofauna, fewer macrofaunal taxa, and reduced condition of epifaunal suspension feeders. Unfortunately, there was limited overlap in species composition between intertidal vs. subtidal habitats, preventing a large number of species-specific comparisons of response across habitats. The common bivalve *Nucula hartvigiana* and the orbinid polychaete *Scoloplos cylindrifer* declined as a result of terrigenous sediment deposition in both intertidal and subtidal habitats. However, trends were weak and/or site-specific in one study or the other. *Heteromastus filiformis* clearly declined at Site MI in the subtidal study, but was not negatively affected by terrigenous sediment in the Whitford intertidal study.

The persistence of the terrigenous deposits also differed in intertidal and subtidal habitats. We hypothesized that the terrigenous materials would be much more susceptible to resuspension in the subtidal realm and might be dispersed away from the experimental plots within hours. However, the terrigenous sediment was clearly visible 30 days following deposition, longer than it remained in place in the intertidal zone. The energy from wind waves may be particularly strong in intertidal habitats, especially as the tide first begins to innudate the flats. In contrast, wave energy did not penetrate to the seabed at our subtidal sites, except during a particularly intense storm coming from the east-northeast (30+ knot sustained winds and choppy sea surface conditions). Furthermore, once the subtidal deposits were covered by a thin layer of silt, they may have been effectively sealed off from bottom water movements that can transport and resuspend sediment particles. Wind waves are thought to promote the break-up and removal of terrigenous deposits in intertidal areas (Norkko et al. 2002, Thrush et al. in press), but such factors may be less important in moderately deep or protected subtidal habitats.

Another difference between the experiments conducted in intertidal and subtidal habitats was the thickness of the terrigenous layers. While we are confident we applied an appropriate amount of slurry to create deposits of 3 and 7 mm thick, the terrigenous sediment never fully de-watered and compacted when applied subtidally. On Day 1, the material appeared as a dense liquid slurry that rested on the seabottom. While difficult to measure accurately, the deposits were obviously much deeper than 3 or 7 mm.

Despite the much greater depositional thickness, the terrigenous material did not appear to create an impenetrable cap on the surface of the subtidal sediment, as it can do in the intertidal. In the subtidal plots at both sites, burrowing animals began re-excavating their holes immediately following the simulated depositional event, ejecting the foreign sediment. In the proximity of such burrows, the underlying sediments probably remained irrigated and oxic, and despite the relatively thick terrigenous layers, perhaps fewer animals were smothered outright. Even the *Echinocardium*, which may have come to the surface for oxygen, were likely killed by predators once they were exposed on the surface of the plots, rather than having succumbed to effects of the sediment deposits directly. Similar gaping by infaunal bivalves and the potential for elevated predation on stressed individuals was also noted in the Okura experiment (Norkko et al. 2002).

We suspect that inputs of terrigenous sediment from coastal catchments are pulsed and correlated to major storm events. Strong rains erode sediment from hills in the catchment, and flow volumes increase with increasing rainwater run-off, further eroding creek and river banks. Our physical instrument arrays provided additional insight into the role of storms, in that storms can dramatically alter hydrodynamics in an estuary and thus influence the behaviour of terrestrial sediments loaded to them. While storm-driven rain may supply terrigenous sediment to an estuary, storm-driven winds may keep the material in suspension for a greater length of time, thus increasing the potential for offshore movement. While the energy from small wind-waves did not penetrate to the seabed during the calm periods (U_{sigb} values <2.5 cm/sec), orbital bed velocities increased 5- to 10-fold during the storm. Storm associated wave-energy was correlated to increased suspended sediment concentrations as well, signalling that fine particles will not settle out until the storm winds abate. When terrigenous materials are loaded to an estuary during a windy and rainy storm, the estuarine benthos may receive proportionally more of the coarse sediment fraction (coarse particles will settle out relatively quickly) while the coastal benthos outside the estuary will likely get finer materials. This may explain observations of the Mahurangi monitoring programme, which has demonstrated increasing proportions of fine sands in the subtidal zone (Cummings et al. 2003a) during a period when sediment loading has probably increased.

4.3 Conclusions and context

Results from this study have expanded our knowledge about the effects of terrigenous sediment on coastal marine resources in the Auckland Region. Performed in subtidal habitats, these experiments provide insight into the response of coastal soft-sediment communities that are both spatially extensive and ecologically important. The Auckland Region is fortunate to contain many diverse and productive subtidal near-shore habitats. However, with land use change associated with human population expansion, combined with steep catchments and a rainy climate, sediment run-off from land to sea is an increasing threat to the Auckland Region, not only to intertidal flats, but to the subtidal coastal realm as well.

In the multifaceted study we performed, the results of several components were consistent: the diverse coastal community was more sensitive to terrigenous sediment than the estuarine community we studied. The estuarine organisms were not immune to the effects of sediment, however. Beyond a critical threshold, they declined markedly as well.

Impacts on small macrofauna indicated that terrigenous sediment is biologically deleterious, as has been demonstrated in previous intertidal studies. However, the statistically significant impacts on large organisms (*Atrina, Aaptos, Styla, Echinocardium*) are particularly noteworthy. These organisms, by virtue of their sizes and densities, can enhance the vertical relief of relatively flat sedimentary habitats, creating settlement microhabitats and hiding places for numerous fish and invertebrate species (Thrush et al. 2001, Thrush et al. 2002). These species may affect sediment biogeochemistry as well, by altering boundary flows and, in the case of *Echinocardium*, through bioturbation and particle displacement. The filter feeders create biodeposits, which can enrich food and microbial activities in their immediate vicinity, in turn affecting macrofaunal biodiversity. The broad-scale loss of such key species as a result of sediment deposition, elevated turbidity, or other stressors is a significant threat to the functioning of Auckland's coastal marine ecosystems.

The results of this experiment extend the ambit of ecological concern into the coastal subtidal region, especially in areas that contain sensitive communities and species. The risk to these systems must be judged against threat posed by terrestrial sediment addition and transport. The significant effects on feeding and condition documented in this study and earlier ones (e.g., Ellis et al. 2002) suggest that a gradual degradation in biodiversity and ecosystem functioning is possible if terrigenous sediment disturbances increase in magnitude or frequency.

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