CHAPTER 6: ASSESSING VEHICLE IMPACTS ON THE BEACH-FACE INTERSTITIAL ENVIRONMENT USING MEIOFAUNAL COMMUNITIES

1. Introduction

The interstitial environment of sandy beaches is the small-scale habitat that exists in the space between the grains of sand, and is inhabited by a group of animals known as the meiofauna. These organisms are defined as those metazoan organisms that can pass through a sieve (typically 0.5 or sometimes 1mm mesh) designed to retain the macrofauna (Mare 1942), but are trapped on a smaller (typically 53μm) sieve that separates the meio- and microfauna (e.g. single-celled protozoans; Fenchel 1978). Because of this classification, some protozoans (specifically larger ciliates and foraminiferans) may be included in sampling for meiofauna (Fenchel 1978).

Interstitial environments can be disturbed by any factor that alters the sediment-matrix properties and thus affects the processes of water infiltration and interstitial flow, such as the application of detergents for the cleaning of oil spills or by pollution of the interstitial environment by fine mineral particles, sewage or heated effluent discharge (Webb 1991).

Meiofaunal organisms display a number of traits that make them useful bioindicators of environmental health (Kennedy & Jacoby 1999; De Ley *et al.* 2006). These communities are highly diverse and abundant, with ubiquitous distributions, much more so than the macrofauna, thus making them a better candidate for a potential bioindicator. Meiofauna tend to have short generation times and are direct developers, so environmental impacts that affect a community may be mirrored in subsequent generations in the same location. Meiofauna are also sedentary, and have a direct reliance on the sediment and interstitial waters (i.e. where pollutants adhere), and show rapid responses to environmental perturbations that affect these aspects of their habitat, making them excellent potential indicators of sediment disturbance. Meiofaunal communities have been used as an indicator of marine anthropogenic disturbances (e.g. Schratzberger *et al.* 2000). Marine meiofaunal communities respond rapidly to ‘pulse’ environmental disturbance, such as once-only sediment reworking or beach-cleaning, with decreased densities and altered community structures observed, but then recover very quickly, within one tidal cycle (Sherman & Coull 1980; Gheskiere *et al.* 2006), thus also potentially masking effects if sampling occurs too late after the disruptive impact. Press disturbances may have a more long-lasting impact. For example, it was shown that tourism, via increased trampling, had an impact on the high-shore zone of European sandy beaches, by negatively affecting the meiofaunal abundance, diversity and community structure at heavily-used beaches when compared with lightly-used beaches nearby (Gheskiere *et al.* 2005).

In addition to population- or community-level comparisons, the subset of meiofaunal nematodes may be used to determine the level of environmental disturbance via an examination of the life history and functional diversity traits of the nematode community (Bongers 1990; Bongers & Bongers 1998), a technique that has been successfully applied to detect environmental impact of various anthropogenic disturbances on communities of free-living marine nematodes (Bongers *et al.* 1991). The feeding habits of many species of free-living nematodes are well known (Yeates *et al.* 1993; Bongers & Bongers 1998), and can be determined *a priori* from an examination of the physical structure of the specimen’s buccal cavity (i.e. mouth, see Wieser 1953; Jensen 1987). Additionally, many free-living nematofaunal species have been described on a life-history spectrum from opportunist or *r*-strategists through to persisters or *K*-strategists (Bongers 1990). Thus, a community maturity index is calculated by determining the ratio of colonisers to persisters (the ’*C-p*’ ratio; Bongers 1990). By combining the maturity index and trophic group classifications for communities of nematodes, it is possible to better understand the diversity, structure, maturity and function of the nematode community and interpret any anthropogenic impacts upon it (Bongers & Bongers 1998).

Earlier chapters of this thesis have investigated vehicle impacts on the physical environment (Chapters 3-4) and wrack-associated macrofaunal communities (Chapter 5) of the study beaches. Few impacts of vehicles on measured physical variables were found; however, vehicles were found to significantly affect macrofaunal populations. In this chapter, the potential for the meiofaunal community to act as a bioindicator of disturbance will be used to assess whether vehicles affect the physical environment of the beach face, which could not be detected with gross measures of the profile characteristics, sediment grain sizing or compaction. At the same time, impacts of vehicles on the meiofaunal community itself will also be assessed.

Thus, the aim of this study was to determine if these meiofaunal communities were impacted by vehicles on beaches and if they could be used to detect environmental impacts of vehicles on the sand body of the study beaches that could not be clearly detected using sediment analysis or morphodynamic comparisons.

2. Methods

Study site

The meiofaunal communities of all beaches included in the main study (Chapters 1, 3 & 5; see Fig. 1.3) were sampled three times (corresponding to seasonal sampling occasions used in earlier chapters related to times of peaks and lows in vehicle usage; see Chapter 1) for the mid-shore meiofaunal community between August 2007 and March 2008. The initial, mid-winter sampling occasion was undertaken during August 2007. Subsequent sampling times (pre- and post-summer) were associated with seasonal sampling occasions on these beaches for the main study (see Chapters 1, 3 & 5).

Field methods

On each visit, a single sampling location was established on each beach, with five replicate samples, spaced at least 2m apart, in a 1m wide band of the mid-shore zone, collected at each location. The same locations were not sampled on different visits. Processing of samples for assessment of meiofaunal community diversity and abundance is very time consuming, and thus it was only feasible in this study to investigate one zone per beach per visit. The mid-shore zone was selected because it represents a peak in diversity for interstitial meiofauna on sandy beaches (Armonies & Reise 2000) for beaches similar in morphotype to those in the study region (i.e. high-tide reflective and low-tide dissipative, LTT morphotype). The mid-shore is also the zone that receives the greatest amount of vehicle traffic on open beaches in the study region (see Chapter 2, esp. Figure 2.4), hence, if vehicle impacts are felt in the interstitial environment of these open beaches, then they would likely be reflected in the meiofaunal communities of the mid-shore zone. For each location, five replicate sediment cores (diameter 3cm, to depth 9cm; total vol. = 60mL) were collected for investigation of the meiofaunal community. Meiofauna inhabiting surface sediments (i.e. <9cm depth) were deemed to be more likely to be affected by vehicle actions than those inhabiting deep sediments, and so sampling efforts were concentrated on surface sediments. A second set of five sediment cores of the same dimensions were also collected for analysis of surface sediment characteristics (i.e. moisture content, grain-size distribution & bulk density). All sediment and meiofaunal cores were placed in sealed plastic jars and packed on ice for transport, then stored at -20°C upon return to the laboratory (this was not found to cause deterioration of the organisms). Five replicate measures of surface-sediment penetration resistance (kg.cm^{-2}) were taken per site using a pocket penetrometer (Geotester pocket penetrometer). Percolation rate of the sediment was determined by measuring the time taken for a known volume of seawater, poured into the top of a plastic core (diameter 11cm; surface area = 380.13cm^{2}), to completely percolate into the sediment; with percolation rate then expressed in mL.cm^{-2}.s^{-1} (based on method described by Bale & Kenny 2005) Finally, vehicle and pedestrian activity on the study beach at the time of sampling was assessed by counts as per the methods detailed in Chapters 2 and 3.

Laboratory methods

Meiofaunal samples were defrosted in batches of five for processing, by overnight refrigerated storage at 4°C. The Ludox flotation method was used to extract meiofauna (Somerfield & Warwick 1996). Samples were placed in a 500mL measuring cylinder, which was then filled to 500mL with fresh water and inverted 5 times before standing to allow the sediments to settle. The water supply used was pre-checked and confirmed to be free of meiofaunal organisms. The supernatant was then carefully poured (so as to prevent sediments from being decanted) through a pair of sieves, first a 500µm sieve, designed to retain the macrofauna, and then a 53µm sieve, to retain the meiofauna. This process was repeated a further nine times for a total of 10 inversions and decantations per sample, then the remaining sediment in the cylinder was checked for meiofauna under a dissection microscope (under 63x magnification). Any macrofauna retained on the 500µm sieve were identified to species level where possible and then stored in 70% ethanol solution. Material retained on the 53µm sieve was then washed with Ludox TM (diluted to specific gravity 1140) into 250mL beakers and allowed to stand for 30 minutes, before the supernatant was carefully decanted through the 53µm sieve. The Ludox TM solution was then poured back into the beaker with the residual material and allowed to stand for a further 30 minutes. The material retained on the 53µm sieve was washed with tap water (pre-checked to ensure that it did not contain meiofaunal organisms) into a clean 250mL beaker. After the second 30 minute standing in Ludox TM solution, the supernatant was again carefully decanted through the 53µm sieve and the residual checked under the dissection microscope for meiofaunal organisms (under 63x magnification). The beaker containing the material retained from the first decantation after Ludox TM flotation was also poured through the 53µm sieve and rinsed with pre-checked tap water to remove Ludox TM solution. A glycerol-alcohol solution (5 parts glycerol: 25 parts 70% ethanol: 70 parts pre-screened tap water) was used to displace water from the sieve contents before the sieve contents were carefully poured into small wells using the glycerol-alcohol solution. Samples were then placed in a drying oven on low heat (30°C) overnight to evaporate the water and alcohol, leaving the meiofauna preserved in pure glycerol. Meiofauna in pure glycerol were then transferred using a gull feather quill (used because of its hydrophobic properties) onto prepared slides and mounted as per methods described by Somerfield and Warwick (1996). Samples were not further sub-sampled; entire samples were put on slides. Staining was not required as organisms were easily observed on slides. Meiofaunal organisms were counted and identified on each slide using a compound microscope (100 – 400x magnification). Meiofauna (excluding nematodes) were identified to Family level where possible (at least Phylum or Sub-Phylum in most instances) using Higgins & Thiel (1988). Crustacea (Subclasses Copepoda and Ostracoda) were further identified where possible using Dole-Olivier *et al.* (2000), and mites (Order Acari/Halacaroidea) were also done using Bartsch (2006). Nematodes were identified to genus where possible using Platt & Warwick (1983; 1988) and Warwick *et al.* (1998). Nematodes were also assigned to feeding guilds based on Wieser (1953) and Jensen (1987).

Sediment samples were defrosted in batches of five for processing, by overnight refrigerated storage at 4°C. Samples were placed in dried (24h at 80°C), pre-weighed alfoil containers and weighed to 4 decimal places to obtain a sample wet weight. Sediment samples were then dried (24h at 80°C) and reweighed to obtain a sample dry weight. Moisture content and bulk density estimates were obtained using formulae described by Bale and Kenny (2005). Each sediment sample was then processed for grain-size distribution statistics (mean grain size and sorting) as per the methods for laser diffraction analysis, described in Chapter 3.

Statistical methods

All data were analysed using version 11 of the SYSTAT software package (univariate analyses) or version 6 of the PRIMER and PERMANOVA+ software package (multivariate statistics). Targeted comparisons were made between beaches (i.e. open v. closed beaches) and within Bays with multiple access sections (i.e. Aldinga and Moana Bays, each with three sections), analysed separately for each seasonal sampling occasion (3 occasions) and also with all three seasonal sampling occasions combined.

All sediment variables, and also the meiofaunal abundance and species richness, were square-root transformed to achieve normality prior to conducting ANOVA tests. Differences in the measured sediment variables, meiofaunal abundance and species richness between beaches were investigated using 3-factor mixed-model nested ANOVAs with Beaches (a random factor with 2 levels; Moana & Sellicks versus Port Willunga & Maslin) nested in access Types (a fixed-factor with 2 levels; Open versus Closed) and Seasonal sampling occasions (a fixed-factor with 3 levels; mid-winter, pre- and post-summer), with five replicate samples per beach. Differences in measured variables within multiple-access Bays (i.e. among sections of different vehicle access Types: a fixed-factor with 3 levels; Aldinga Bay: seasonal, bollarded and open; Moana Bay: closed, open and bollarded) and

Seasonal sampling occasions (as for between-beach comparisons) were investigated using 2-factor ANOVAs, with five replicate samples per beach. Relationships between meiofaunal abundance or species richness and the measured sediment variables and relationships amongst the various sediment variables were investigated using scatterplots and regression statistics where appropriate.

Multivariate analysis of the total meiofaunal community or the subset nematode assemblage was also done separately for each seasonal sampling occasion and also for the three occasions combined. Meiofaunal community data were entered as abundances per core by species (not as a per-unit-area density) and the entire data set was 4th-root transformed to reduce the influence of a few, very large abundance counts for a handful of species. An approach, combining PERMANOVA, PERMDISP and multi-dimensional scaling (hereafter MDS) ordination plots, as used in Chapter 5 of this thesis for macrofauna, was used again here to investigate differences in the total meiofaunal community, and the subset nematode community. By doing this, I was able to separate spatial effects from differences in the level of variability between or among groups. Differences in meiofaunal community structure between-beaches were investigated using three (i.e. separately for each seasonal sampling occasion) mixed-model PERMANOVAs with Beaches (a random factor with 2 levels) nested in access Types (a fixed-factor with 2 levels; open versus closed beaches), with five replicate samples per beach. Differences within-beaches at Aldinga and Moana Bays were investigated using a series of three (i.e. again separately for each sampling occasion), one-way PERMANOVAs testing differences among sections of different vehicle access Types (a fixed-factor with 3 levels; Aldinga Bay: seasonal, bollarded and open; Moana Bay: closed, open and bollarded). For both between- and within-beaches analyses, differences among the three seasonal sampling occasions were investigated by adding the additional factor Season (a fixed-factor with 3 levels; mid-winter, pre- and post-summer; orthogonal to the other factors) to the respective designs above.

PERMDISP was used to separate differences in variability between or among levels of factors in PERMANOVA (see Chapter 5), and MDS ordination plots were generated to investigate separation of groups that would indicate different meiofaunal or nematode communities between or among factor levels (e.g. vehicle access Types). SIMPER procedures were used to investigate similarities (i.e. among replicates) within groups and differences between groups of samples and so to identify species that typified groups or contributed significantly to observed differences between groups.

BEST (BIO-ENV procedure) was used to identify measured sediment variables that best explained the observed patterns separately for the total meiofaunal community and the subset nematode community structure between- and within-beaches, and also overall (i.e. all study beaches combined). Skewed variables (i.e. bulk density, penetration resistance and percolation rate) were first log-transformed ($\log_{10}$) then environmental data were normalised. BEST (BIO-ENV) procedures were also used to determine if the overall meiofaunal community structure was explained by underlying patterns in the subset nematode community. Patterns in the overall meiofaunal community may have been related to the abundance of particular nematode feeding groups, for example, nematode predators. RELATE was used to determine if there was any relationship between the total meiofaunal community and the feeding guild structure of the nematode community (Clarke & Gorely 2006), using 4th root transformed Bray-Curtis similarity matrices (dummy variable = 1).

3. Results

Meiofauna

In total, 135 meiofaunal cores over the three sampling visits to the nine study beaches were collected and processed. Unfortunately, once mounted, 41 slides were damaged when unseasonably hot weather caused the wax seal between the slide and cover slip to melt, resulting in some of the contents leaking out. Pre-summer samples were worst affected, with just over half of those slides thus leaking. Almost a third of mid-winter slides and only some (~10%) of the post-summer slides leaked. Only one slide (Maslin rep. 3 Nov. 07) was completely lost (i.e. all slide contents leaked out). Following this, all slides were checked for leaks, resealed where required and stored at 4°C to prevent any further damage. In total, 7,519 meiofaunal organisms were thus collected and identified, representing 73 species (Table 6.1). Nematode worms were by far the most diverse and abundant group of organisms on the study beaches, comprising over half the total number of individuals (4,643 individuals) and species (40 spp.) collected. All feeding guilds described by Wieser (1953) and Jensen (1987) were represented. Also collected were representatives of the Cnidaria (3 spp.; 1347 individuals); Copepoda (4 spp.; 792 individuals) and Foraminifera (3 spp.; 446 individuals), and ten other groups in lower abundances (Table 6.1). Meiofaunal abundance was generally greatest during the pre-summer sampling occasion, except for Normanville and Moana North where peak abundances occurred during the post-summer occasion, and Moana Bollards where abundance peaked during the mid-winter occasion, with abundances at Maslin Beach always being relatively low (Figure 6.1).

Sediment variables

In total, 135 separate (from meiofaunal cores) sediment samples were processed over the three seasonal sampling occasions (n = 45 per season). Sediment mean grain sizes ranged from 117 to 252µm (mean 204 µm), with the vast majority (97.8%) of samples classifying as fine sands (i.e. 126-250µm; Blott & Pye 2001). Only two samples were slightly finer (117 & 122µm – very fine sand), both from Maslin Beach in the pre-summer sampling period, and one from Aldinga Bollards (post-summer) were classified as slightly coarser (252µm - medium sand). Sorting values ranged between 0.377-1.007 (mean 0.528; i.e. symmetrical to coarse skewed; Blott & Pye 2001), with the majority of samples being coarse-skewed (83.0%). Sediment percent moisture content ranged between 2.2-16.6% (mean 9.7%). Bulk density estimates fell within a very narrow range of values (1.2-2.2g/mL; mean 1.5g/mL). Surface strength showed a much greater range of values (penetration resistance (PR); 0.9-6.0 kg/cm^2; mean 3.3kg/cm^2). Likewise, there was a great range in the values for percolation rate of water into the sediment body (3.1-48.7mL/cm^2/s; mean 10.5mL/cm^2/s). There was a weak but significant negative relationship between surface strength (PR) and percolation rate ($\log_{10}$-transformed), suggesting that as surface sediments became firmer, the percolation rate slowed (Figure 6.2).

Table 6.1: Meiofaunal species richness (SR) and total number of individuals (Abun.) by taxonomic groups for all three sampling occasions. Damaged nematodes were only counted and included in abundance counts if they still had their head attached, and these specimens remain unidentified. Feeding guilds are also included for nematode worms. Some nematodes remained unidentified because these were either partial specimens (heads only) or obscured by detritus. See Appendix Table 6.1 for detailed nematode classifications.

Kingdom	Phylum	Sub-Phylum	Super-Class	Class	Sub-Class	Order	Sub-Order	Family		SR	Abun.
Protista	Granoloreticulosa	Sarcodina				Foraminiferida	Rotaliina			3	446
Animalia	Cnidaria			Hydrozoa						3	1347
	Platyhelminthes			Turbellaria						3	61
	Gastrotricha									2	86
	Nematoda			Adenophorea	Enloplia	Enoplida	Enoplina			29	3966
						Monhysterida				5	49
						Chromadorida				6	90
									Unidentified	n/a	538
									TOTAL	**40**	**4643**
								Feeding Guilds:	Deposit	22	2132
									Epistrate	6	1077
									Omnivore	2	10
									Predator	9	106
									Scavenger	1	772
	Mollusca			Bivalvia						1	17
	Annelida			Polychaeta		Canalipalpata		Protodrilidae		2	11
	Arthropoda	Insecta				Coleoptera				2	29
		Crustacea		Malacostraca		Isopoda				2	5
				Maxillopoda	Copepoda					4	792
					Ostracoda					4	27
		Chelicerata	Arachnida			Halacaroidea				2	23
		Unknown								3	6
	Tardigrada									2	26
TOTAL										**73**	**7519**

Figure 6.1: Mean (±SE; *n* = 5 cores per beach per sampling occasion) meiofaunal abundance observed on each beach and sampling occasion. Note the y-axis scale is the same across all nine plots and extends to the maximum replicate value.

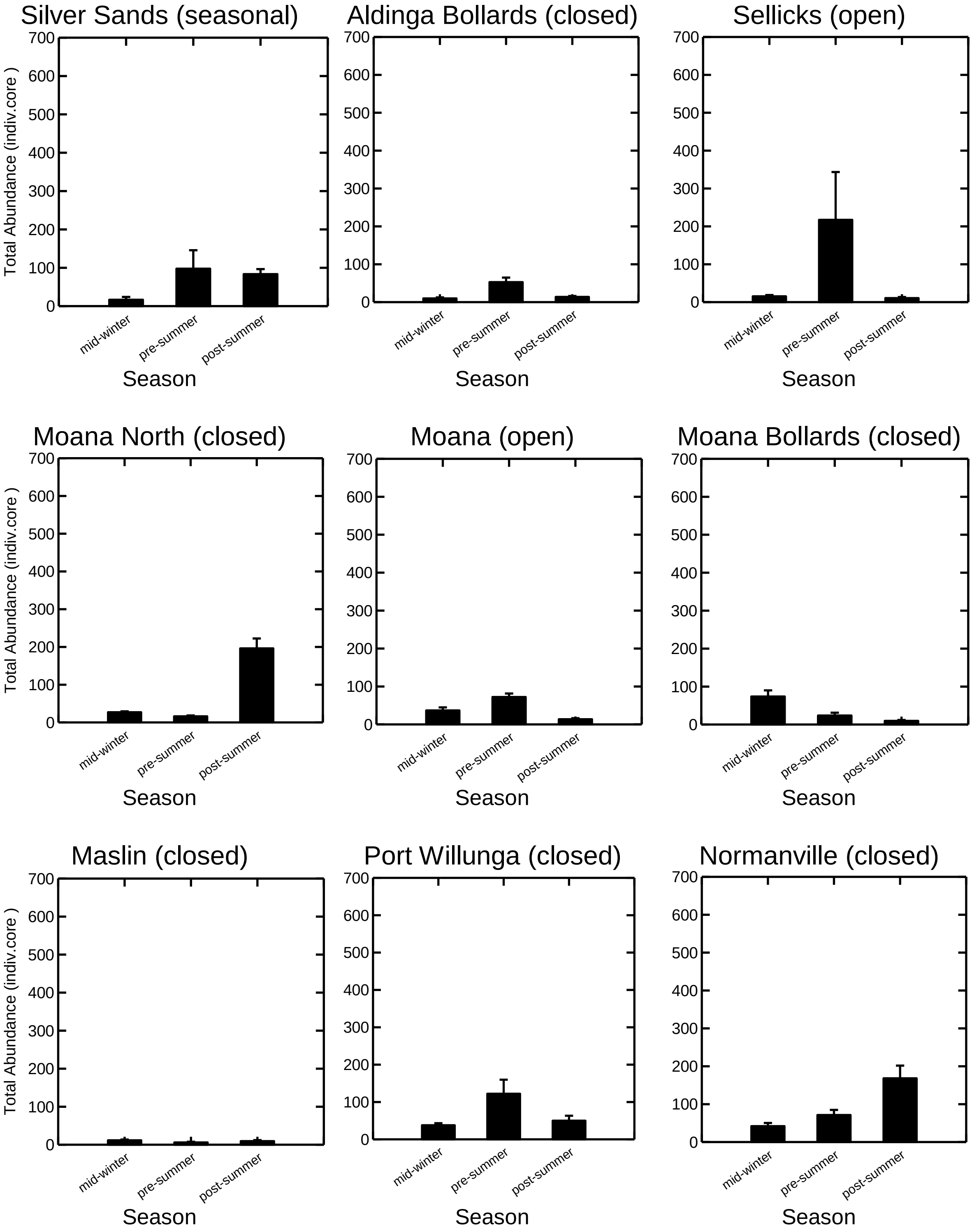
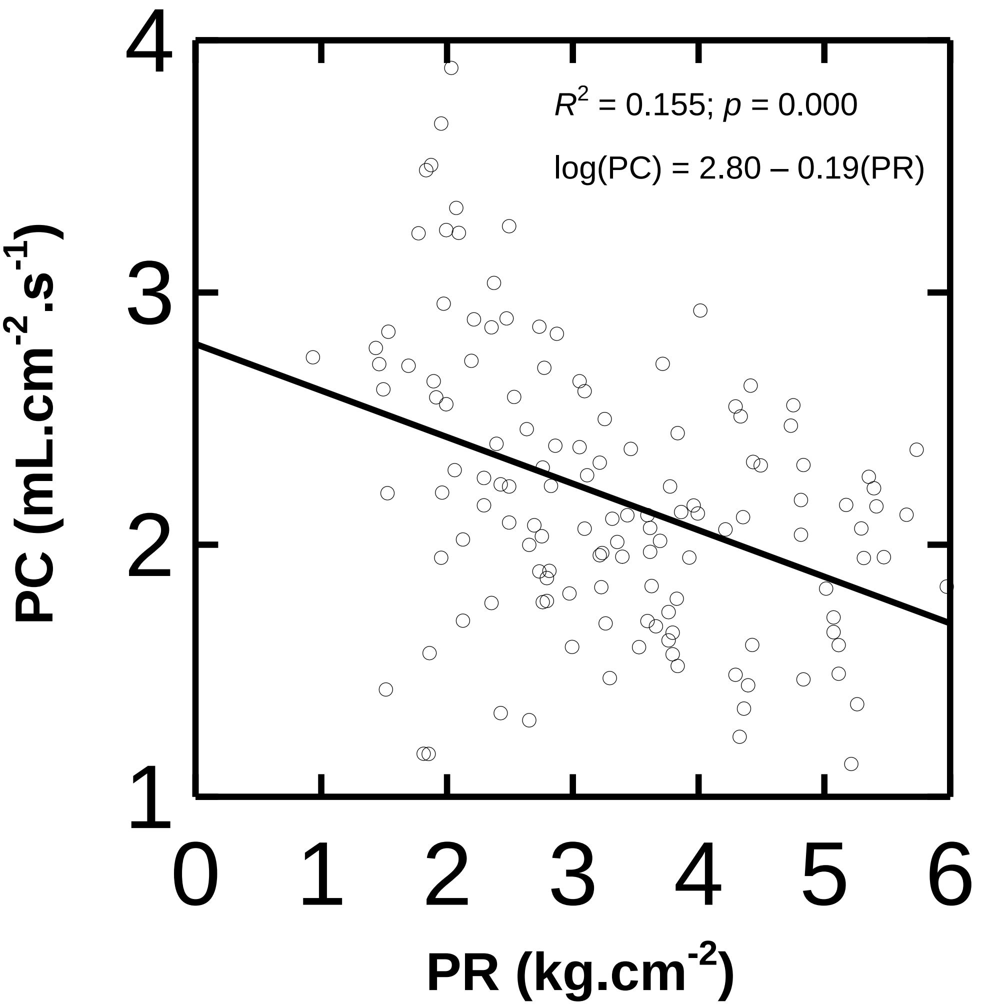


Figure 6.2: Scatterplot showing a weak but significant negative relationship between percolation rate (PC: $\log_{10}$ transformed; y-axis) and penetration resistance (PR; x-axis) values for the same samples (*n* = 135). The regression equation relates PC and PR.



Comparisons between-beaches

There was no significant difference in mid-shore zone width (in metres) between beaches of open and closed type (source = T: $F_{1,2} = 0.026$; $p > 0.05$), although there was significant small-scale spatial variation among beaches (source = B(T): $F_{2,23} = 4.093$; $p < 0.05$). Sediments in the mid-shore zone on closed beaches were finer (mean grain size = 153.77±2.93μm) than sediments on open beaches (mean grain size = 217.67±3.11μm), a difference that was statistically significant (source = T: $F_{1,2} = 45.90$; $p > 0.05$), in combination with significant interacting temporal and small-scale spatial variation (source = S*B(T): $F_{4,48} = 4.394$; $p < 0.01$). However, sediments from both open and closed beaches fell within the range of fine sands (126-250μm; Blott & Pye 2001), and thus differences in mean grain size may not be biologically significant. Sediments on both open and closed beaches were coarse-skewed (Blott & Pye 2001), with no significant differences in other sediment variables (i.e. sorting, percent moisture content, penetration resistance or percolation rate) between access Types, only some significant spatial and temporal variation (i.e. source S*B(T) significant at $p < 0.05$ for $F_{4,48}$). There was no significant difference in sediment bulk density for any factor. There was a weak but significant negative relationship between the sediment percent moisture content and percolation rate (log-transformed) ($n = 135$; $R^2 = 0.368$; $p = 0.000$); however, because the relationship was not strong, both variables were included in the multivariate analyses. There was significant interacting temporal and small-scale spatial effects (i.e. source S*B(T) significant at $p < 0.05$ for $F_{4,47}$) for both abundance and species richness of meiofauna, that appear to be unrelated to vehicle access Types (i.e. T was not significant as a main effect or as part of an interaction effect). Summary tables of these univariate tests of between-beaches comparisons are available as Appendix Table 6.2.

For each sampling season, there were significant small-scale spatial variation in meiofaunal communities among beaches (i.e. significant B(T) for all three seasons individually and over all three seasons combined; Table 6.2a) but not between access Types (i.e. T not significant as a main effect or as part of an interaction effect) detected by PERMANOVA. Although stress values are relatively high (especially for the total meiofaunal community

Table 6.2: Summary of multivariate results for permutations based comparisons of the total meiofaunal community a) between-; and within-beaches at b) Aldinga and c) Moana Bays. Light grey shading indicates that that factor was not applicable for the particular PERMANOVA test (i.e. there is no Season term for tests of just one season). PERMDISP results indicate significant differences in variability among factor levels. Significance values are indicated with asterisk (*p* (permutations-based) values: * < 0.05; ** < 0.01; *** < 0.001). Blank = NS.

a) Between-Beaches (Open v Closed)

PERMANOVA:

Source	Mid-Winter	Pre-summer	Post-Summer	Overall
Season				*
Type				
Beach(Type)	***	***	***	***
Season*Type				
Season*Beach(Type)				***

PERMDISP:

Source	Mid-Winter	Pre-summer	Post-Summer	Overall
Season				
Type		***		
Beach		***		

b) Within-Beaches (Aldinga Bay)

PERMANOVA:

Source	Mid-Winter	Pre-summer	Post-Summer	Overall
Season				***
Type	*	***	***	***
Season*Type				***

PERMDISP:

Source	Mid-Winter	Pre-summer	Post-Summer	Overall
Season				*
Type				

c) Within-Beaches (Moana Bay)

PERMANOVA:

Source	Mid-Winter	Pre-summer	Post-Summer	Overall
Season				***
Type	***	***	***	***
Season*Type				***

PERMDISP:

Source	Mid-Winter	Pre-summer	Post-Summer	Overall
Season				*
Type	*			

during the mid-winter sampling occasion), MDS ordination plots of meiofaunal community data for each sampling occasion show clear groupings based on Beaches but not Types (Figure 6.3). Samples from Maslin Beach were significantly more variable (as detected by PERMDISP) than those from other beaches for the pre-summer sampling occasion; Table 6.2a), a result that likely drove a significant difference in variability that was observed between vehicle access Types for the pre-summer sampling occasion (i.e. closed more variable than open beaches; Table 6.2a). Maslin Beach samples displayed poor average similarity amongst themselves for all three seasons when tested by SIMPER, especially for the pre-summer sampling occasion (Table 6.3), but particularly so during the pre-summer sampling occasion, when samples from Maslin Beach were also highly dissimilar from other beaches (Table 6.3). There were low levels of within-group similarity for samples collected from the two open beaches, Moana and Sellicks, during the post-summer sampling occasion (Table 6.3).

The average similarity of samples from closed beaches was lower than that of open beaches (Table 6.4) and the average dissimilarity among samples from open versus closed beaches was high (average dissimilarity = 60.78; Table 6.4). Meiofaunal communities on open and closed beaches were both typified by high abundances of Cnidarian sp. 1 and the nematode, *Chromadora* sp. (Table 6.4). The two species (i.e. Cnidarian sp. 1 and *Chromadora* sp.) with the highest contributions to similarity among samples within Type groups (Table 6.4) also had reasonably high contributions to dissimilarities between Types (ranked 8th and 1st in order of contribution, respectively; Table 6.4). Many species selected as having high contributions to dissimilarity among samples from different vehicle-access Types were similar in abundance between open and closed beaches (Table 6.4). Two nematode species, *Paradontophora* sp. 1 and *Retrotheristus* sp., with relatively high individual contributions to dissimilarity between access Types (i.e. 7.5% and 6.9%, respectively) were more abundant on open beaches than closed ones (Table 6.4). There were also more partial nematode worms collected on open beaches relative to closed ones (Table 6.4). BEST (BIO-ENV) analysis revealed that there were no consistent trends in relationships between meiofaunal communities and the measured sediment variables

Figure 6.3: Multidimensional scaling (MDS) ordination plots of the total meiofaunal assemblage (left hand column) and the subset nematode assemblage (right hand column) for beaches open versus closed to vehicles, plotted separately for each sampling occasion. Square symbols indicate open beaches, circle symbols indicate closed beaches. The four individual beaches are indicated by colours (dark blue: Moana; aqua: Sellicks; red: Maslin; pink: Port Willunga).

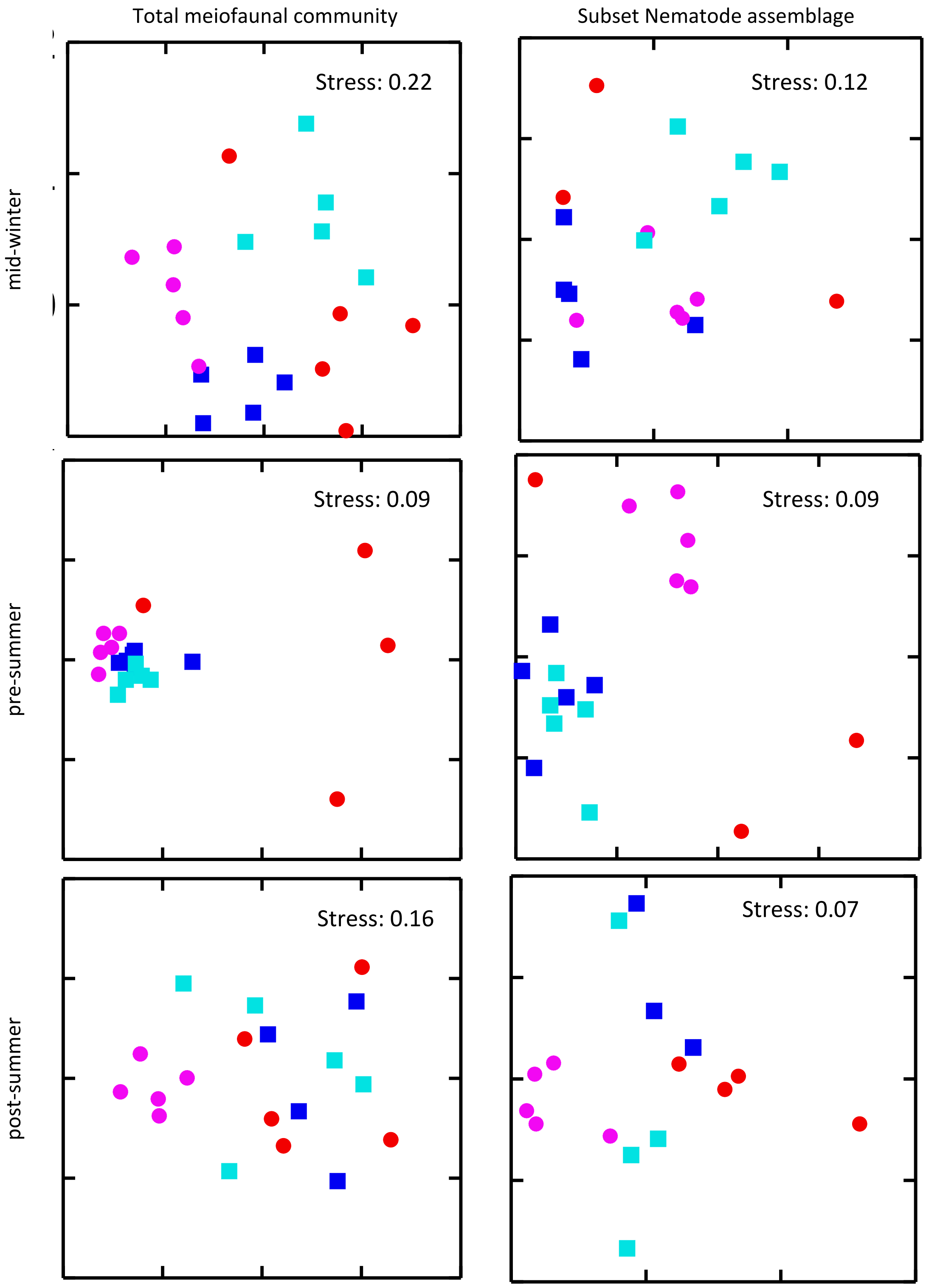


Table 6.3: Results of the SIMPER analysis showing average similarities within beaches (light-grey cells) and average dissimilarities between beaches (unshaded cells) for beaches either open (Sellicks & Moana) versus closed (Maslin & Port Willunga) to vehicles. Dark grey cells are duplicate (mirror image) comparisons and are hence left blank.

Season	Beach	Sellicks	Moana	Maslin	Port Willunga
Mid-winter	Sellicks	61.17			
	Moana	57.43	62.55		
	Maslin	56.07	56.35	48.35	
	Port Willunga	60.67	44.43	60.28	63.90
Pre-summer	Sellicks	65.7			
	Moana	45.33	62.86		
	Maslin	79.05	80.81	16.47	
	Port Willunga	59.30	53.48	80.37	62.74
Post-summer	Sellicks	46.06			
	Moana	50.68	55.86		
	Maslin	55.48	49.77	52.10	
	Port Willunga	58.74	63.12	64.79	67.86

Table 6.4: SIMPER comparisons between-beaches open or closed to vehicles showing species (ranked in order of contribution to similarity or dissimilarity for (a,b) within- and (c)between-group comparisons, respectively). Average (shortened throughout to Ave.) abundance values are 4th-root transformed. All fauna listed here had SD > 1.

a) Group: Within-Closed beaches
Ave. similarity = 40.79

Rank	Species	% Contribution
1	Cnidarian sp. 1	48.8
2	*Chromadora* sp.	15.63
3	Foram sp. 2	6.98
4	Nematode head only	4.99
5	*Steineria* sp.	4.04
6	*Paradontophora* sp. 1	2.92
7	Copepod sp. 3	2.56
8	Halacaroidea sp. 2	1.9
9	Chromatdorida sp. 1	1.88
10	Enlopid sp. 2	1.85

b) Group: Within-Open beaches
Ave. similarity = 52.39

Rank	Species	% Contribution
1	Cnidarian sp. 1	43.95
2	*Chromadora* sp.	12.72
3	*Retrotheristus* sp.	7.96
4	Nematode head only	7.34
5	*Paradontophora* sp. 1	7.18
6	*Steineria* sp.	4.93
7	Foram sp. 2	3.58
8	Copepod sp. 3	3.37

c) Group: Between Closed v Open
Ave. dissimilarity = 60.78

		Ave. Abundances			Ave.	(%)
Rank	Species	closed	v	open	dissimilarity	Contribution
1	*Chromadora* sp.	1.11	>	1.00	6.74	11.09
2	Nematode head only	0.56	<	0.81	5.04	8.28
3	Foram sp. 2	0.60	>	0.54	4.76	7.84
4	*Paradontophora* sp. 1	0.42	<	0.83	4.54	7.47
5	*Retrotheristus* sp.	0.08	<	0.94	4.22	6.94
6	*Steineria* sp.	0.52	<	0.64	3.71	6.11
7	Nematode whole obsc.	0.14	<	0.50	3.04	5.00
8	Cnidarian sp. 1	1.69	<	1.71	2.93	4.82
9	Enlopid sp. 2	0.29	>	0.19	2.69	4.43
10	Foram sp. 1	0.29	>	0.19	1.98	3.27

between-beaches open or closed to vehicles for any of the three seasonal sampling times (Table 6.5a). Patterns in meiofaunal community structure between open and closed beaches was only well explained (i.e. a rho (ρ) value both high and significant indicating a strong correlation between data sets) by the measured sediment variables in the pre-summer sampling time (Table 6.5a). After this, relationships between the meiofauna and measured sediment variables broke-down, becoming non-significant (Table 6.5a).

Comparisons within Bays: Moana and Aldinga Bays

Again, sediment variables and meiofaunal abundance and species richness were square-root transformed to meet the assumption of normality for ANOVA. There was significant variability, both temporally and between vehicle-access Type sections (i.e. spatially) for all sediment variables in both Bays. There was a significant Season*Type interaction for sediment mean grain size, percent moisture, bulk density, penetration resistance and percolation rate and significant Seasonal differences for sediment sorting for both Bays. Visual inspection of the data (i.e. using bar graphs not shown here) revealed no trends in the individual sediment variables between beach sections for both Aldinga or Moana Bay in relation to Seasons (i.e. sampling occasions), vehicle access Types or even the location of the beach section along the bay (i.e. whether section was at the middle or end of the bay). There were significant interactions between Seasonal sampling occasions and vehicle-access Types for meiofaunal abundance and species richness in both Bays; however, there were no consistent trends in meiofaunal abundance or species richness between vehicle-access Types within Bays or Seasonal sampling occasions seen upon visual inspection of the data. Summary tables of these univariate tests of between-beaches comparisons are available as Appendix Table 6.2.

Trends for differences among sections of the beach at Aldinga Bay were apparent during the mid-winter sampling occasion, with the open section grouping apart from the closure sections; however these patterns broke-down in summer, when vehicle traffic intensified. The total meiofaunal community also showed significant temporal (i.e. among S sampling occasions) and spatial (i.e. among sections with different vehicle access T)

Table 6.5: BEST (BIO-ENV) results showing the top three correlations between patterns in sediment variables (abbreviated for mean grain size: MGS; bulk density: BD; penetration resistance: PR; and percolation rate: PC) and meiofaunal community structure for samples from a) open and closed beaches; b) Aldinga Bay; c) Moana Bay; and d) all samples combined, analysed separately for each seasonal sampling occasion (MW: mid-winter; PS: pre-summer; PT: post-summer). Ticks (✓) indicate sediment variables selected to explain patterns in meiofaunal community structure for each correlation. Blanks indicate variables not selected. Bold values and double ticks indicate significant correlations between sediment variables and meiofaunal community structure. Grey shading indicates significant correlations that also explained a high portion (i.e. >50%) of the variance in the relationship between the meiofaunal community structure and the measured sediment variables. Bulk density (BD), penetration resistance (PR) and percolation rate (PC) were $\log_{10}$-transformed to improve sample distributions.

Comparison	Season	ρ (rho)	*P*	MGS (µm)	Sorting	Moisture (%)	BD (g/mL)	PR (kg/cm^2)	PC (mL/cm^2/s)
a) Between beaches: Open v Closed *n* = 20 (per season)	**MW**	**0.357**	**0.002**		✓✓				
		0.342			✓				✓
		0.325			✓			✓	
	PS	**0.829**	**0.001**	✓✓		✓✓			✓✓
		0.823		✓		✓		✓	✓
		0.818				✓			✓
	PT	0.194	0.144		✓			✓	
		0.183			✓			✓	✓
		0.183		✓	✓			✓	
b) Within beach: Aldinga Bay *n* = 15 (per season)	MW	0.228	0.201		✓				
		0.135		✓	✓				
		0.119			✓			✓	
	PS	0.393	0.100	✓	✓				✓
		0.392		✓	✓			✓	✓
		0.370		✓	✓				
	PT	**0.547**	**0.002**	✓✓	✓✓	✓✓		✓✓	
		0.545		✓		✓		✓	
		0.537			✓	✓		✓	

Table 6.5: cont.

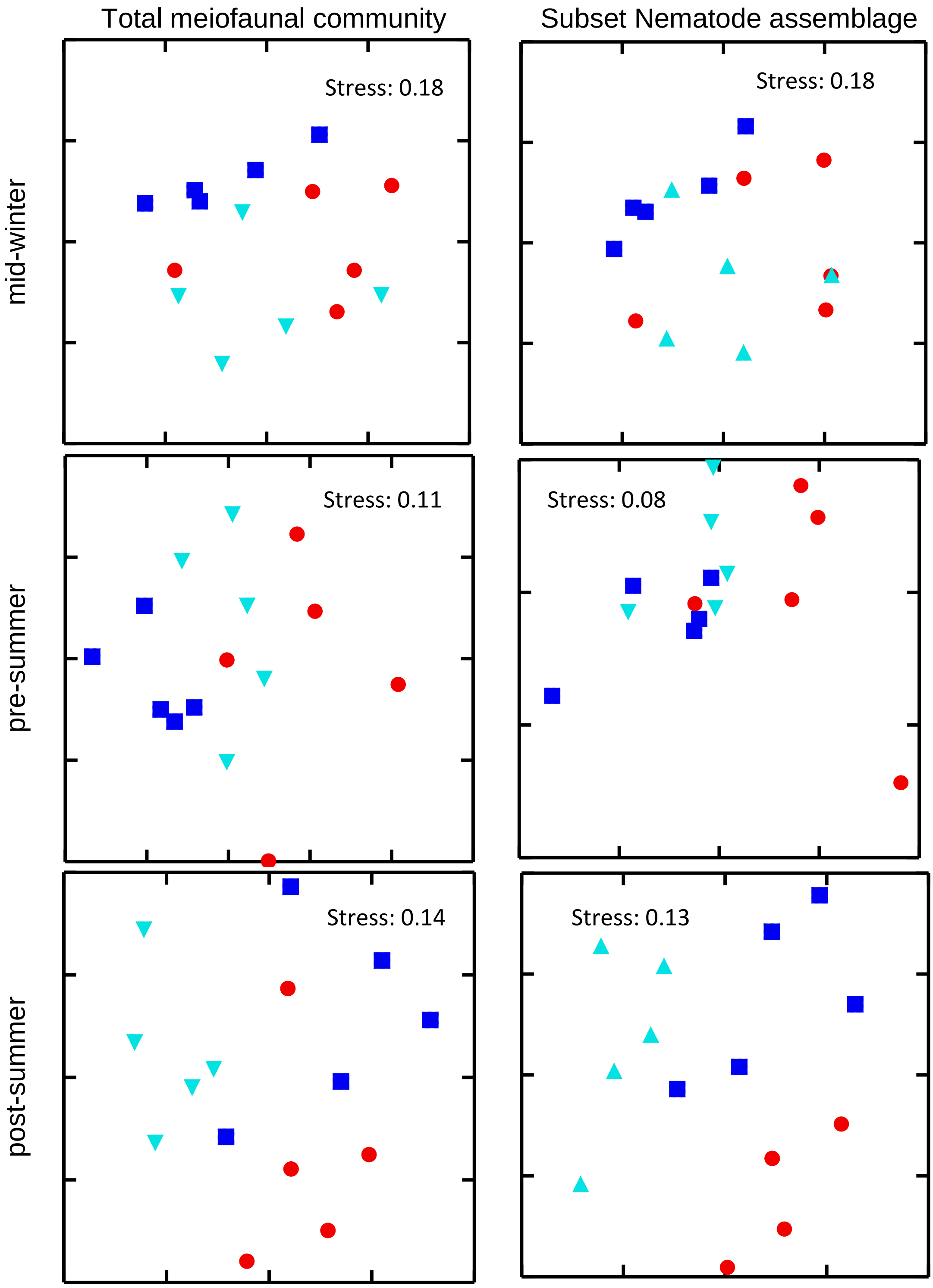
Comparison	Season	ρ (rho)	*P*	MGS (µm)	Sorting	Moisture (%)	BD (g.mL^{-1})	PR (kg.cm^{-2})	PC (mL.s^{-1})
c) Within beach: Moana Bay *n* = 15 (per season)	**MW**	**0.675**	**0.001**	✓✓		✓✓		✓✓	✓✓
		0.674		✓	✓	✓		✓	✓
		0.674				✓		✓	✓
	PS	**0.595**	**0.001**	✓✓		✓✓			
		0.579		✓	✓	✓			
		0.548		✓		✓			✓
	PT	**0.391**	**0.025**	✓✓			✓✓		
		0.370		✓	✓		✓		
		0.361		✓	✓		✓	✓	
d) OVERALL *n* = 135	**ALL**	**0.282**	**0.001**			✓✓			
		0.279		✓		✓			
		0.274				✓			✓
Overall by seasonal sampling occasions *n* = 45 (per season)	**MW**	**0.280**	**0.001**		✓✓	✓✓		✓✓	
		0.275			✓	✓		✓	✓
		0.274			✓			✓	
	PS	**0.563**	**0.001**	✓✓		✓✓			✓✓
		0.544		✓		✓		✓	✓
		0.539		✓		✓			
	PT	**0.243**	**0.001**			✓✓			✓✓
		0.239			✓	✓			✓
		0.233			✓	✓	✓		✓

variability in both Bays when tested by PERMANOVA (Table 6.2b). There were significant differences between Type sections for all three Seasonal sampling occasions, which can be seen clearly in the MDS ordination plots (Figure 6.4) and over all occasions combined for Aldinga Bay (Table 6.2b). The seasonal and bollarded closure were both significantly dissimilar from the open section during the mid-winter sampling occasion (source: T Pseudo-$F_{2,12} = 2.316$, $p < 0.05$, Table 6.2b, Figure 6.4), when vehicles are not permitted on the seasonal closure and vehicle usage of this section is low (see Figure 2.5). During the pre-summer sampling occasion, all three sections were significantly dissimilar from each other (source: Type Pseudo-$F_{2,12} = 4.507$, $p < 0.001$, Table 6.2b, Figure 6.4). However, these trends based on vehicle access appear to break down by the post-summer sampling occasion; although there are significant differences based on Type (Pseudo-$F_{2,12} = 5.546$, $p < 0.001$, Table 6.2b), there was no significant difference in the similarity of the bollarded and the open sections (Table 6.2b; Figure 6.4), indicating spatial differences that are unrelated to vehicle access. Over all three seasonal sampling occasions (i.e. combined) there were significant Season*Type effects (Pseudo-$F_{4,36} = 3.980$, $p < 0.001$, Table 6.2b) and patterns for differences among access Types were the same as those for the seasons analysed individually.

There were no significant differences in the level of variability of meiofaunal communities from closed versus open beaches when analysed by PERMDISP (Table 6.2b). When the three seasonal sampling occasions were combined, there was a significant difference in the level of variability among samples from the three separate seasons, with greater variability among samples from the post-summer sampling occasions relative to both the mid-winter and pre-summer occasions (Table 6.2b).

Again, BEST (BIO-ENV) analysis revealed that there were no consistent trends in relationships between meiofaunal communities and measured sediment variables between the three seasonal sampling times for Aldinga Bay beach sections (Table 6.5b). Unlike results for comparisons made between beaches, the best correlation between sediment variables and the observed patterns in meiofaunal community structure for Aldinga Bay was seen for the post-summer sampling occasion (Table 6.5b).

Figure 6.4: Multidimensional scaling (MDS) ordination plots of the total meiofaunal assemblage (left hand column) and the subset nematode assemblage (righthand column) for Aldinga Bay beach sections, plotted separately for each sampling occasion. The three sections are indicated by symbol colours and shapes (dark blue squares: open; red circles: bollarded closure: aqua triangles: seasonal closure).



Like at Aldinga Bay, there were significant differences in the meiofaunal and subset nematode community structure among sections with different vehicle access Types at Moana Bay that appeared to reflect vehicle usage on these sections (i.e. the open section being significantly dissimilar to both closures) for the mid-winter and pre-summer sampling occasion (Table 6.2c, Figure 6.5). Again these differences broke down after the period of intense vehicle usage (i.e. by the post-summer sampling occasion, Table 6.2c), with the bollarded and open sections being similar to each other, and the closed northern section grouping away from these other two (Figure 6.4). Over the three sampling occasions combined, there is a significant Season*Type interaction effect (Pseudo-$F_{4,36} = 8.404$, $p < 0.001$, Table 6.2c).

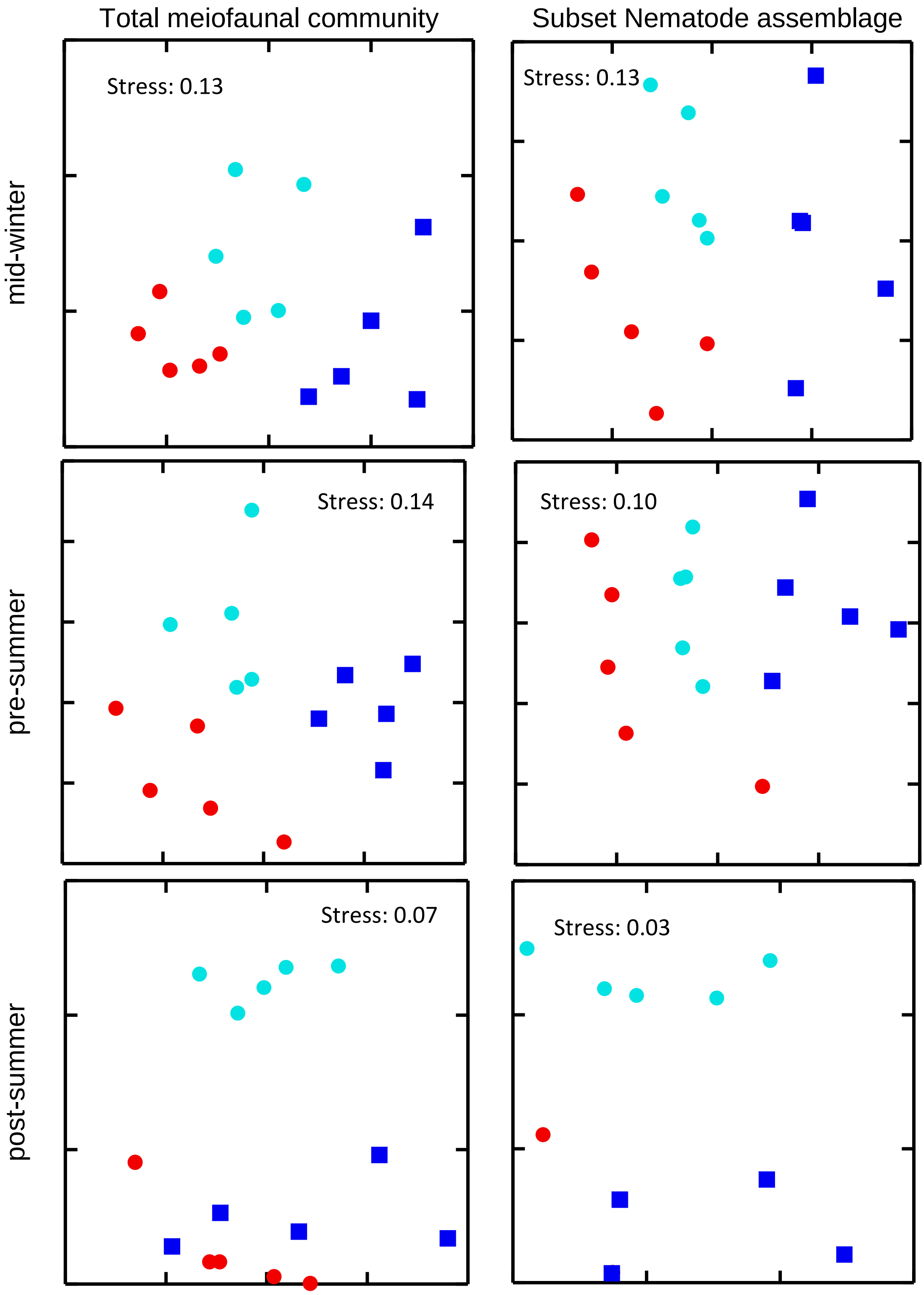
There were significant differences in the level of variability among samples from different access Types during the mid-winter sampling occasion at Moana Bay detected by PERMDISP ($F_{2,12} = 5.172$, $p < 0.05$, Table 6.2c), with variability among samples from the bollarded section being significantly lower than both the open and closure sections (Figure 6.4).When data from the three seasonal sampling occasions were combined there was significantly higher variability in samples collected during the mid-winter sampling occasion (Table 6.2c).

BEST (BIO-ENV) results indicated that there were better correlations between sediment variables and observed patterns in meiofaunal communities (Table 6.5c) relative to those observed for Aldinga Bay, and there was also some consistency between seasons for the mid-winter and pre-summer sampling occasions (Table 6.5c).

Environmental variables contributing to meiofaunal community structure

There were no clear relationships between the individual sediment variables and total meiofaunal abundance or species richness, but there were some trends for increasing meiofaunal abundance with increased moisture content of the sediments and with decreased percolation rate (i.e. the weakly negatively-related variables; see Figure 6.2). Across all samples, patterns in meiofaunal communities were also not well explained by the measured sediment variables when tested by BEST (BIO-ENV) (Table 6.5d). Although statistically significant ($p = 0.001$), the sample statistic (rho = 0.282)

Figure 6.5: Multidimensional scaling (MDS) ordination plots of the total meiofaunal assemblage (lefthand column) and the subset nematode assemblage (righthand column) for Moana Bay beach sections, plotted separately for each sampling occasion. The three sections are indicated by symbol colours and shapes (dark blue squares: open; red circles: bollarded closure: light blue circles: closed section).



for the highest-ranking correlation (selecting percent moisture content only) was quite low, indicating a relationship that explains little of the variation between meiofaunal communities and the measured sediment variables. Mean grain size and the moisture content of the sediments were frequently selected in significant and strongest (i.e. high rho values) BEST (BIO-ENV) correlation analyses for between- and within-beach comparisons (Table 6.5a-d). Penetration resistance and percolation rate (both log-transformed) were also frequently selected in the higher-ranking correlations (Table 6.5a-b).

Nematode community structure and feeding groups

Nematodes were divided into five feeding guilds based on buccal cavity structure. Of the 4,097 nematodes identified (see Appendix 6.1), most were either deposit (52% of nematodes) or epistrate (26.3% of nematodes) feeders (Jensen 1987). Both these guilds feed on diatoms, by either swallowing them whole or cracking their frustules and ingesting the contents (Jensen 1987). Deposit feeders were the most abundant feeding guild on both closed and open beaches but there was a higher abundance of epistrate and scavenger feeders on beaches open to vehicles, relative to closed ones (Figure 6.6a). However, this difference was not significant when tested by PERMANOVA on Euclidean distances of these univariate data (because data could not be transformed to normality for univariate tests) for either epistrate feeders (Pseudo-$F_{1,2}$ = 2.805; p = 0.170) or scavengers (Pseudo-$F_{1,2}$ = 1.329; p = 0.662). There were no apparent patterns in feeding guild abundances in within-beaches comparisons, except perhaps for increased abundance of deposit feeders and scavengers in the closed section at Moana Bay (Figure 6.6b-c).

Patterns in the subset nematode assemblage between- and within-beaches (Table 6.6) resembled closely those of the total meiofaunal community (see Table 6.4; Figure 6.3-4). Nematode feeding guild structure explained approximately 28%of the variation (ρ = 0.53; p = 0.0001), which is unsurprising, given that the nematode community is the largest subset of this total meiofaunal community. There were some differences between the two sets of results for the within-beaches comparisons; differences seen for between-beach comparisons were only changes in significance level rather

Figure 6.6: Mean abundance (±SE; untransformed data) of each of the five nematode feeding guilds identified by Jensen (1987) along x-axis a) between-beaches either open (Moana and Sellicks) versus closed (Maslin and Port Willunga) to vehicles; or, within beaches at b) Aldinga, and c) Moana Bays. Note different scales for the y-axis across the three plots.

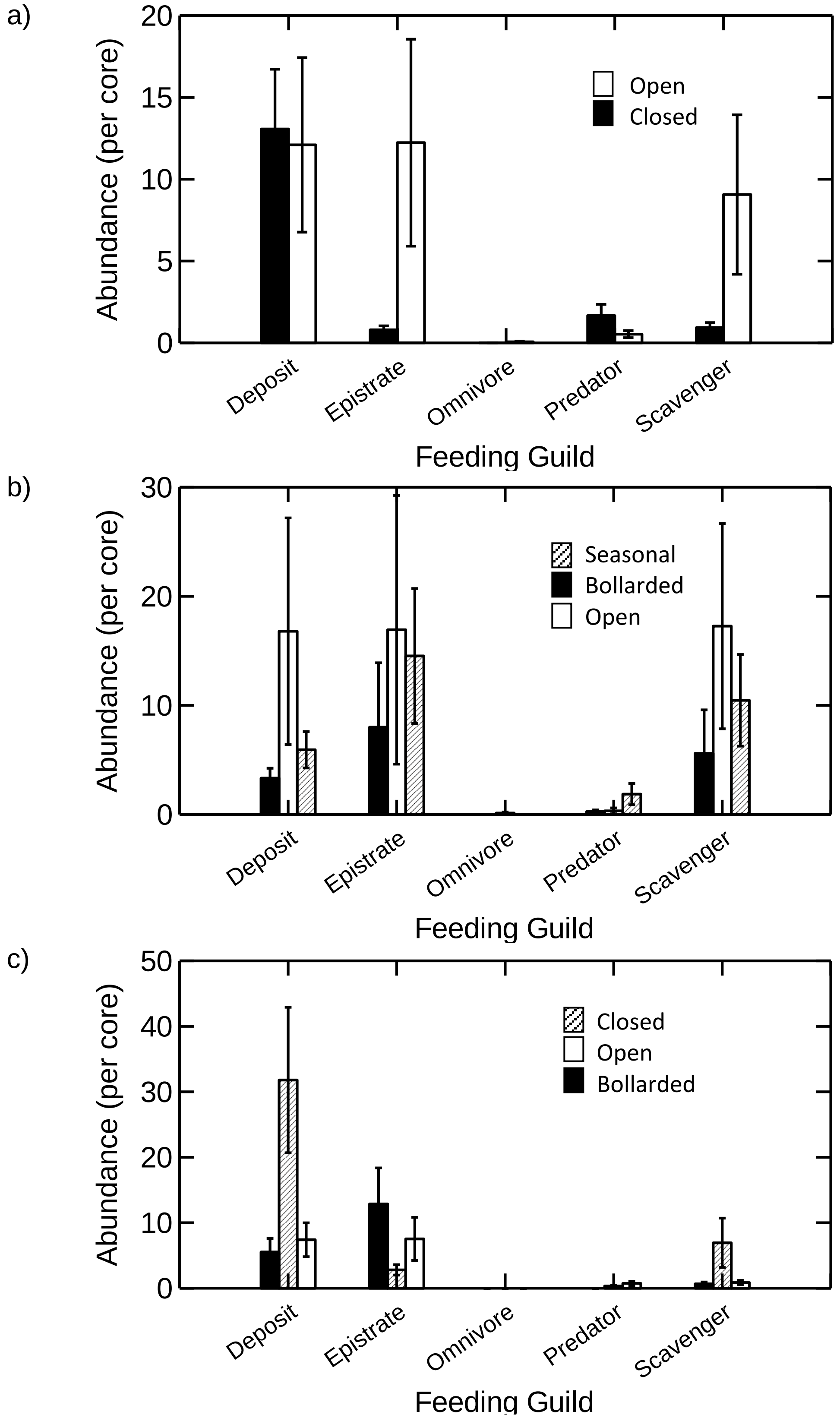


Table 6.6: Summary of multivariate results for permutations based comparisons of the nematode assemblage a) between- or within-beaches at b) Aldinga and c) Moana Bays. Light grey shading indicates that that factor was not applicable for the particular PERMANOVA test (i.e. there is no Season term for tests of just one season). Blank = NS. PERMDISP results indicate significant differences in variability among factor levels. Significance values are indicated with asterisk (*p* (permutations-based) values: * < 0.05; ** < 0.01; *** < 0.001).

a) Between-Beaches (Open v Closed)

PERMANOVA:

Source	Mid-Winter	Pre-summer	Post-Summer	Overall
Season				*
Type				
Beach(Type)	***	***	***	***
Season*Type				
Season*Beach(Type)				***

PERMDISP:

Source	Mid-Winter	Pre-summer	Post-Summer	Overall
Season				
Type		**		
Beach		*		

b) Within-Beaches (Aldinga Bay)

PERMANOVA:

Source	Mid-Winter	Pre-summer	Post-Summer	Overall
Season				***
Type		**	***	***
Season*Type				***

PERMDISP:

Source	Mid-Winter	Pre-summer	Post-Summer	Overall
Season				PS<(Pt=MW)**
Type	*			

c) Within-Beaches (Moana Bay)

PERMANOVA:

Source	Mid-Winter	Pre-summer	Post-Summer	Overall
Season				***
Type	***	***	***	***
Season*Type				***

PERMDISP:

Source	Mid-Winter	Pre-summer	Post-Summer	Overall
Season				**
Type				**

than factors becoming non-significant or significant (compare Tables 6.4 & 6.6). There was no significant difference in nematode community structure among sections of different access types at Aldinga Bay for the mid-winter sampling occasion detected by PERMANOVA; however, samples collected from the open section were significantly less variable than those collected from either closure section (Table 6.6). That there was such close similarity between results for the total meiofaunal community and the nematode subset suggests that patterns in the nematode assemblage are driving observed patterns in the total community.

4. Discussion

Differences in the meiofaunal community (i.e. as detected by PERMANOVA) were only consistently observed for within-beaches comparisons. Differences in sediment characteristics and meiofaunal abundance, species richness and community structure between beaches (i.e. open versus closed beaches) were inconsistent by vehicle-access Types and appear to be driven by site-specific factors that are unique to each particular beach nested within Type. So, from between-beaches comparisons, there were no clearly apparent effects of vehicles on the interstitial environment or meiofaunal community, except for a break-down in relationships between these communities and the measured environmental variables (i.e. by the post-summer sampling occasion; BEST-BIOENV results), and some differences in nematode feeding guilds abundance. Likewise, there were no differences in sediment variables or meiofaunal abundance and species richness among sections of both Aldinga and Moana Bays that appeared to be related to vehicle access differences. However, there were some trends for differences in meiofaunal community structure among sections for both Bays, and again relationships between the meiofaunal community structure and measured environmental variables appeared to brake-down after intensive vehicle use. Looking at only meiofaunal abundance for each beach section by seasons (Figure 6.1), there was apparent no consistent pattern based on vehicle access. For example, there were not fewer meiofaunal organisms on open sections or beaches relative to closed ones. Thus it would seem that differences observed in the meiofaunal community among the different beach sections at Aldinga and Moana Bays may not be related simply to vehicle access but that instead the effect of vehicles on this group of organisms may be the possible break-down of relationships between these communities and environmental variables. Field and lab experiments, targeting relationships between meiofaunal community structure and environmental variables and the effects of intensifying vehicle traffic on these relationships, could be used to further investigate whether intensifying vehicle usage of a beach resulted in the break-down in relationships between meiofaunal community structure and the measured environmental variables.

Relationships between the meiofaunal community and measured environmental variables were stronger at Moana Bay than Aldinga Bay. It is possible that these relationships take time to develop following vehicle exclusion, although these are still weakly developed even at Moana Bay where closures have been in effect for more than 15 years. Although there was a tendency for relationships between environmental variables and meiofaunal communities to potentially break down with intensifying vehicle usage of open beaches, these environmental variables did not explain patterns in either the total meiofaunal community or nematode subset very well in general. Only moisture content, penetration resistance and percolation rate showed any real range in values, and, unsurprisingly, these were also the only variables commonly selected to explain meiofaunal community patterns (Table 6.5). Other variables (e.g. mean grain size, sorting) had narrow ranges of values. It was deliberately attempted to hold sediment variables more or less held constant across beaches, by specifically focussing sampling efforts only in the mid-shore zone, thus making it easier to isolate vehicle impacts, especially since these sediment variables were not found to be affected by vehicles on beaches in earlier chapters (see Chapter 3). Given the relatively small values for rho obtained from the BEST(BIOENV) analyses, it is likely that there is some other factor/s or sediment variable/s, that have not been measured in this study (e.g. salinity, pH, wave exposure, predation, competition, etc.; Kennedy & Jacoby 1999; Rodriguez *et al.* 2003) are important in determining the structure of these meiofaunal communities. Mean grain size and the concentration of trace metals were found to be important in determining meiofaunal community structure in off-shore locations in the UK (Schratzberger *et al.* 2000).

Sediment grain size is one factor that will determine the size of interstitial spaces, thus affecting pore connectivity and hence water circulation, with generally poorer circulation in finer sediments (Webb 1991). Vehicles were not found to affect sediment grain-size distributions, and in this study, the range of values for mean grain sizes among beaches was small. Unsurprisingly, there were also no significant differences in percolation rates of water into the sediments of beaches open versus those closed to vehicles. So, although both these variable were measured, neither was likely to be selected as important in determining the structure of meiofaunal communities. High concentrations of trace metals, attributed to sewage sludge and polluted water discharge into the Burbo Bight, UK, were correlated with lower diversities of meiofauna in sediments (Schratzberger *et al.* 2000). Measuring the concentrations of trace metals was beyond the scope of this study of a particular anthropogenic impact that was perceived to be physical (i.e. disturbance via sand movement, compaction etc.) rather than chemical in nature. Additionally, the location of the study sites along the metropolitan coastline of a large city like Adelaide suggests that any differences in concentrations of trace metals would be on a regional scale, and differences among beaches in a small area were likely to be negligible, and unrelated to vehicles. The effects of hydrocarbon pollution (e.g. engine oil) on meiofaunal communities on beaches open to vehicles has not, to my knowledge, been investigated.

Patterns in the total meiofaunal community were well explained by patterns in nematode feeding guild assemblages (i.e. the rho value obtained by RELATE was both relatively high and significant); however, this result is in line with the great relative abundance of nematodes compared with other meiofaunal organisms in the samples. Dominance of nematodes in the meiofaunal community is frequently reported (e.g. in USA: Sherman & Coull 1980; UK: Schratzberger *et al.* 2000; Spain: Rodriguez *et al.* 2003; and Belgium: Gheskiere *et al.* 2006). Unfortunately, identifying nematodes to species level proved difficult (only 8 of 40 species could be identified to genus level) and planned comparisons of the nematode-community maturity index between- and within-beaches were thus not possible. Nonetheless, there were some interesting patterns in the abundances of organisms fitting into the five feeding guilds identified by Jensen (1987); patterns of abundance differed between within- and between-beaches comparisons. Between beaches, deposit feeders were the most abundant guild on both open and closed beaches but there were more scavengers and epistrate feeders on open beaches than closed ones (Figure 6.6a). Open beaches also had a higher count of damaged nematodes (Table 6.4). It is unlikely that this result was due to handling problems (i.e. damage during collection or processing) because of the bias in the number of damaged nematodes from just one beach type; if handling was an issue, relatively equal numbers of damaged nematodes across samples from different beaches would be expected instead. Thus it is possible that there are more scavenging opportunities on open beaches due to increased availability of carrion, because some meiofauna may be damaged or killed by vehicle passes. This hypothesis could be tested experimentally by repeatedly driving over an area and sampling the meiofauna after a predetermined number of vehicle passes, as has been done for macrofaunal organisms (see Wolcott & Wolcott 1984; van der Merwe & van der Merwe 1991), and so determining whether there is increased damage to individuals with increasing application of vehicle traffic.

A number of slides were found to have leaked during a weekend of unseasonably hot weather (see Results); however, the leakages in most cases were very minor, and the majority of slides that were resealed were treated as a precautionary measure (i.e. there was no evidence that slide contents had leaked, just the chance that, without repair, some contents may have been lost in the future). Only one slide was damaged beyond repair, and, although a number of slides from the mid-winter sampling occasion were damaged, there was no apparent bias towards damage to slides from any particular beach. Thus, it is not expected that the unfortunate damage to some slides prior to identification and counting of organisms has affected the results of this study.

Negative anthropogenic impacts on meiofaunal assemblages have been demonstrated on sandy beaches previously. Meiofaunal assemblages on tourist beaches in both the Mediterranean and Baltic regions of Europe displayed lower densities, diversities, increased community stress and altered community structure relative to nearby un-impacted beaches (Gheskiere *et al.* 2005), a result that those authors attributed to trampling, coastal development and beach raking, the latter of which both removes organic debris and disturbs beach sediments. Only once in three years was beach cleaning observed on any of the study beaches in southern metropolitan Adelaide, at Moana North, prior to any sampling for meiofauna was conducted, and beach raking is not routinely undertaken on any of these beaches (C. Button, City of Onkaparinga, pers. comm.). Thus, beach raking is not likely to be a significant impact on meiofaunal populations on the study beaches. However, significant reworking and disturbance still occurs due to vehicle use (see Chapter 4) but to high-shore sediments, not on the mid shore. Thus it is possible that vehicle impacts on meiofaunal assemblages may be detected in the high shore, rather than the mid shore, because impacts on the sediment body of the mid-shore zone appear to be minimal (see Chapters 3 & 4). Thus future studies into vehicle effects on high-shore meiofaunal communities may help determine if vehicles can effect this group of beach fauna. Alternatively, impacts may be great but short lived, with rapid recovery of populations after disturbance masking effects. Meiofaunal assemblages elsewhere recover rapidly from pulse-type disturbances, such as once-off beach-raking, when sediments are rewetted by the following high tide (Gheskiere *et al.* 2006). Thus, meiofaunal populations of the mid shore may be disturbed by vehicles but then recover when the intertidal zone is next flooded. It is unlikely that this is the case on the study beaches, because vehicle activity on these beaches is not a one-off event, with repeated disturbance to sediments occurring throughout the year (see Chapter 2).

Further work is needed to determine whether meiofauna (either as individual species or communities as a whole) are useful as suitable candidates for bioindicators of physical disturbance by vehicles on beaches sampled in this study, and on other beaches where vehicle use is an issue. Meiofaunal organisms fulfil some of the desirable characteristics for response indicators to pollution in marine environments (Kennedy & Jacoby 1999) outlined by Ward and Jacoby (1992), and various nematode species have been used successfully as indicators of pollution in other aquatic habitats (Arthington *et al.* 1986; Lorenzen *et al.* 1987). The structure and composition of meiofaunal communities have been identified as useful indicators of environmental pollution in subtidal marine habitats (Schratzberger *et al.* 2000). Meiofaunal communities have also shown some sensitivity to physical disturbances in the high-shore zone on sandy beaches, specifically related to beach raking and tourism (Gheskiere *et al.* 2005; 2006) but do display rapid recovery to small-scale (Sherman & Coull 1980) or short-term (Gheskiere *et al.* 2006) physical disturbances. The distribution of meiofaunal organisms in space (i.e. across or along a beach) is known to be extremely patchy (Kennedy & Jacoby 1999); for example, a high degree of temporal and spatial variability has been shown for nematode communities of other Australian temperate sandy beaches (Nicholas & Hodda 1999; Nicolas 2001). Nematodes are suspended in waters of the near-shore and surf zones by waves and off-shore currents (Hagerman & Reiger 1981), a factor which may contribute to the observed rapid recovery of these communities after small-scale or short term disturbance. Indeed, the nematodes of intertidal beaches may be considered an extension of sub-tidal populations (Nicolas 2001). Further study is needed to determine the linkages and exchange between intertidal and sub-tidal communities of meiofauna on beaches, especially beaches subject to disturbance.

Vehicle disturbance on the beaches studied in this chapter has been continuous over decades on open beaches, with only seasonal variation in intensity of that usage (see Chapter 2). Thus, if vehicles do cause disturbance to the sand-body habitat, then it would be a press-type disturbance, rather than a pulse event (Downes *et al.* 2002), and repeated recovery of meiofaunal communities between multiple disturbance events may be impeded or even impossible. Alternatively, that there were few differences in meiofaunal community structure between beaches open versus those closed to vehicles suggests that these communities may recover completely.

A previous study of the effects of vehicle traffic on meiofaunal communities on beaches found that copepods showed a positive response to vehicle disturbance, with these organisms most likely accumulating in vehicle ruts, attracted by trapped detritus (Bell 2005). In my study, some individual nematode species showed population-level responses to vehicle traffic in between-beaches comparisons, specifically the higher abundances of

Paradontophora sp. 1 and *Retrotheristus* sp. on open beaches, with these two species each contributing relatively highly to the dissimilarity between beaches with different vehicle access (ranked 4th and 5th, respectively, in the SIMPER analysis, see Table 6.4). *Paradontophora* sp. 1 was relatively easy to identify in samples, with clear jaw structure that was quite noticeable and unique. *Paradontophora* sp. 1 was also classified as a scavenger based on buccal cavity structure (Jensen 1987); scavengers were a feeding group that was more abundant on beaches with vehicles in the study region. Given the ubiquitous nature of this species across the beaches sampled in this study, and the ease of identifying this species, assessment of the relative abundance of *Paradontophora* sp. 1 may be one useful tool in a rapid investigation of vehicle impacts on beaches; however, more research is needed to further quantify the response of this species to vehicle disturbance on beaches and find further species so as to develop a suite of potential indicator species.

There were also community-level responses of meiofauna to vehicle presence on beaches, with some differences seen between beaches open versus closed to vehicles based on feeding guild structure (Figure 6.6). But the response of meiofaunal communities to vehicle presence on beaches was inconsistent among sampling times, with no clear patterns observed based on vehicle access either between- or within-beaches (see Table 6.2). There were, however, some patterns for differences in community structure based on vehicle access among sections of the two multiple-access Bays (e.g. see Figure 6.5). This study represents a once-off investigation into the response of meiofaunal communities and the interstitial habitat to vehicle disturbance on beaches. More investigation is needed to further quantify responses of meiofaunal communities to vehicle disturbance and determine if the feeding-guild structure and taxonomic composition of meiofaunal communities may be useful as bioindicators of vehicle disturbance on beaches.

5. Conclusion

There was only limited support for the predictions made in Chapter 1 (see Figure 1.5) that vehicles would negatively affect sediment variables and meiofaunal abundance, species richness and alter meiofaunal community structure. Specifically, the only trend observed was for decreasing strength of the relationship between meiofaunal community structure and the measured environmental variables in both between- and within-beaches comparisons. Overall, this chapter has shown the importance of considering the composition of organisms and their relative abundances rather than simple comparisons of total abundance – differences that may be attributed to vehicle access are only apparent when the abundance of certain groups, either individual species or certain feeding guilds, are considered. Thus the overall aim of this chapter, to assess vehicle impacts on meiofaunal and the interstitial habitat, has been achieved.

Unfortunately, a high degree of variability coupled with the short-term nature of this study have made it impossible to make any firm conclusions regarding the impacts of vehicles on meiofauna, and to determine the overall usefulness of this group of organisms as an indicator for assessing vehicle impacts on the interstitial habitat. However, there is some potential for the use of individual species, namely *Paradontophora* sp. 1, and certain feeding guilds (epistrate feeders and scavengers) of nematode worms to be used as indicators of vehicle disturbance, pending further investigation of their response to impacts. Although the use of meiofaunal communities as indicators of disturbance on beaches is promising, the costs of a large scale investigation, in terms of both time and expense, would be great, especially in comparison to sampling the macrofauna, which also showed clear responses to vehicle disturbance. Thus, while meiofauna may prove useful indicators of vehicle disturbance they may best be used to complement macrofaunal studies, which can be done on a larger scale.