CHAPTER 3: IMPACTS OF VEHICLES ON THE BEACH-FACE AND SEDIMENTS

1. Introduction

Sandy beaches are physically-dominated ecosystems – the dynamics of their physical appearance is closely linked to shifts in abiotic forcing factors, such as patterns in wind and waves, and sediment availability and transport. Any activity or process that can interfere with the natural patterns in these abiotic factors may cause noticeable physical changes in the beach itself.

Vehicles are clearly incapable of influencing factors such as waves, tides or wind regimes. However, vehicle activity on beaches may influence the availability and transport of sediments, via beach flattening, compacting sediments and altering sediment moisture content. Vehicles may cause significant disruption to the sediments of sandy beaches, via rutting of the sand, altering the compaction and/or moisture content of sediments, displacing sand and destabilising surficial crusts. Surface strength (or penetration resistance) indicates the degree of compaction of sediments – more compacted soils generally have a higher surface strength, more force is required to penetrate the surface of the soil. Studies of sediment compaction on intertidal beaches are rare. In unconsolidated sand (approximating high-shore beach conditions), surface strength may decrease with vehicle use, a trend not observed in other soil types (on land) exposed to intense vehicle usage (Wilshire *et al.* 1978; Hosier & Eaton 1980). Bulk density, another proxy for sediment compaction (as sediment becomes more compact its density increases) was shown to increase by an average of 8% in sandy soils exposed to vehicle traffic, even though surface strength of the same soils was shown to decrease, suggesting that vehicles do increase the compaction of unconsolidated sandy sediments but destroy the delicate surface crust that forms over such sediments and offers protection from wind erosion of fine particles (Wilshire *et al.* 1978). Comparison of dune sands from two barrier-island beaches in North Carolina, one widely used by vehicles and the other not, showed decreased surface strength (0.44 compared to 0.96 kg cm^{-2}) but increased strength at 15cm depth (11.28 compared to 4.66 kg cm^{-2}) in the dune system exposed to vehicle activity (Hosier & Eaton 1980). Similarly, reduced surface strength but compaction at depth was observed after experimental application of vehicle traffic on a beach on Fire Island, New York (Anders & Leatherman 1987). Thus there is a general trend for loosening of surface sediments combined sub-surface compaction at depth.

Vehicles can cause significant tracking and rutting of the beach face (Schlacher & Thompson 2008; Schlacher & Morrison 2008; see also Chapter 4, this thesis), which can lead to significant displacement and erosion of sand from the intertidal beach (Anders & Leatherman 1987; Schlacher & Thompson 2008; see also Chapter 4, this thesis for an overview of the effects and implications of sediment displacement and erosion) and cause disruption to (and thus the destruction of) surficial salt crusts on dry, high-shore sands (Wilshire *et al.* 1978). However, unlike the typically dry sands of sand dunes and deserts, the sediments of intertidal beaches are subject to frequent wetting by the tide. The effects of vehicles on the frequently wetted (and hence re-worked) mid- and low-shore sands are likely to be negligible, although increased compaction of moist to wet low-shore sands by vehicles was shown for a Queensland beach (Schlacher *et al.* 2008b). On the other hand, it is possible that there may be effects on dry, unconsolidated high-shore sands, which are only wetted and reworked at times of extreme high-tide which occurs during storm events. By destroying the surficial crust that form on top of the surface of dry, unconsolidated sands, vehicles may indirectly cause increased water infiltration and hence raise the sediment moisture content (Wilshire *et al.* 1978). Alternatively, destruction of the surficial crust may cause result in a higher evaporation rate, thus drying sediments. Further, sand compacted by vehicles may hold more moisture via increased infiltration but moisture flow (and hence flow of oxygen and nutrients) may be slowed by reduced pore space. Direct tests involving the application of experimental vehicle traffic to dune sands have shown that moisture content does not increase in direct response to compaction or other action of vehicles (Kutiel *et al.* 2000). However, comparison of tracks or areas intensively used by vehicles to unused areas have shown that moisture content in dry, unconsolidated sands increases with increased compaction attributed to vehicles (Liddle & Moore 1974; Liddle & Greig-Smith 1975; Wilshire *et al.* 1978), indicating an indirect or delayed effect of vehicles on sediment moisture content.

Vehicle impacts, such as rutting, displacement and resulting erosion and also alteration of compaction and moisture content, all of which may alter the natural pattern of sediment accretion and erosion on a beach, may have the potential to cause changes in other factors such as beach slope, width, height and area of the intertidal sand wedge. Thus, the overriding aim of this study (see Fig. 1.6) was to investigate vehicle effects on the physical environment of the beach (i.e. profiles, sediments etc.), by using a series of between- and within beaches comparisons of univariate and multivariate datasets. Specifically, this chapter will investigate vehicle effects on the beach:

- profile statistics (i.e. beach height, width, slope and cross-sectional area of the intertidal sand wedge);
- sediment characteristics (i.e. mean grain size, sorting, moisture content (%W_a); organic matter content (%OM); percent cobble content); and
- total physical environment, via the use of multivariate statistical techniques.

2. Methods

Study sites and design

All of the nine main study beaches (see Figure 1.3) were included in sampling for physical characteristics (i.e. profile, sediments and compaction) as part of the regular sampling trips using the study design described in Chapter 1.

Profiling

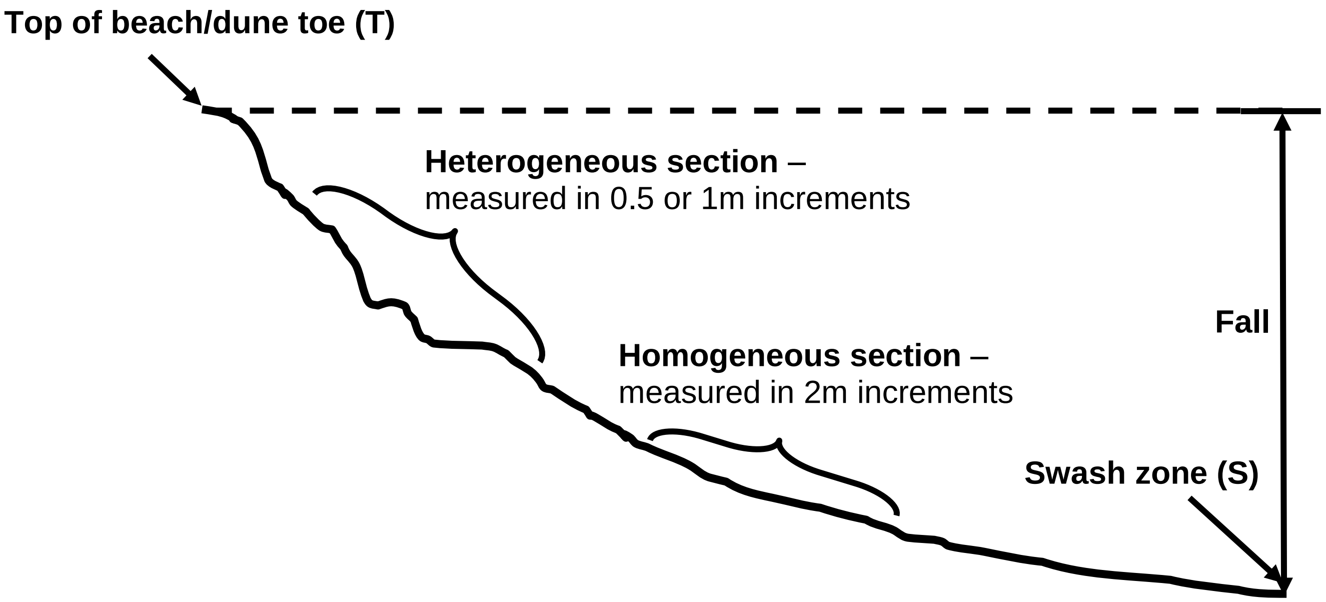
Beach profiling was conducted at transect level, with three replicate profiles measured per beach (i.e. on each of the three haphazardly-established transects; see Chapter 1). Basic surveyors' equipment, including a dumpy level and staff, was used to measure the profile of the beach face in 2m horizontal increments from the top of the beach to the swash zone. For the purposes of this study, 'top of the beach' was defined as either the toe of the foredune or some other defining point in the absence of dunes (e.g. the base of a seawall or cliff). Where there were sudden changes in beach slope (i.e. at the base of a cobble bed or in a runnel or tide pool), increments of measurement were reduced to 1m or 0.5m to capture this higher degree of variability. Beach width (in metres) was measured with the transect tape from the top of the beach to the upper limit of the swash zone, and data from each profile were used to calculate beach fall, slope and the area of the sand wedge forming the intertidal beach at the time of sampling (Figure 3.1).

Sediment sampling

Sediment sampling was done at the level of beach zones, with three zones identified visually on the beach based on moisture content of the sand, i.e. high-, mid- and low-shore (as defined in Chapter 1). Two sediment cores (using 11cm diameter corer to 10cm depth; total sample volume 950.3cm^3) were taken haphazardly from each zone for determining sediment moisture content, grain-size distribution and organic matter content, using the methods and calculations detailed in Bale and Kenny (2005). For the purposes of this study, I was interested in the sediments as they are in the environment, including their carbonate and organic components, so no pre-treatment (i.e. rinsing with water to remove salts, pre-ashing to remove organic matter or washing with acids to remove carbonates; see Bale & Kenny 2005) of the samples for the purpose of removing these components were performed.

Initially, grain-size distribution statistics were obtained by processing sediment samples using test sieve methods (Bale & Kenny 2005). A haphazardly-collected subsample from each sediment core was weighed to obtain wet-weight, dried for 24 hours at 80^{o}C then re-weighed to obtain dry weight after being allowed to cool at room temperature in a desiccator (Bale & Kenny 2005). A stack of six sieves (2mm, 1mm, 500μm, 250μm, 125μm and 63μm) were used to sieve the dried subsample by mechanical shaking for 15 minutes then the fraction of sediment retained in each sieve and in the collection pan was weighed. The fraction-weights (in grams) data obtained were then run through Gradistat software to obtain sediment grain-size distribution statistics (Folk and Ward Method of Moments; mean grain size, sorting, kurtosis and skew; Blott & Pye 2001). The percentage of the sample retained in the collection pan ranged between 0.00-2.06%, with an average of only 0.04%, and thus a separate analysis of the silt-clay fraction was not performed.

Figure 3.1: Hypothetical beach profile showing how measurements were made.



Beach Width = distance (in m) between the top of the beach and swash zone, measured along the beach surface

Fall = difference in beach height between T and S (in m)

Slope = Fall / Beach Width (i.e. rise/run)

Area = $\sum H_n$ for each W_n[†]

[†] W_n = width increment or any given point on transect; either 2m, 1m or 0.5m depending on complexity of beach profile; H_n = height measurement for any given W_n

Samples collected after November 2006 were processed for grain-size analysis using laser diffraction (Malvern Mastersizer with Hydro2000 attachment; 3500 rpm at 7-10% obscuration). Because laser diffraction only requires approximately 10g of pre-dried sediment, after November 2006 only a 60mL sub-sample of homogenised sediment from the core sample was collected rather than returning the entire core to the lab. If the core sample contained cobbles the entire core was still collected to allow measurements of the cobble fraction (i.e. dimensions, percentage of total sample) to be made. Although the Mastersizer instrument is capable of detecting and measuring particles between 0.02μm and 2000μm, particles with a diameter greater than 1mm must be removed prior to processing to avoid damage to the pump of the dispersal unit. Thus, pre-dried sediments (dried for 24h at 80°C) were screened with a 1mm sieve to remove any large grains that could damage the Malvern instrument and this faction was dry weighed as well as total dry weight of the sediment sample. Calculation of the percentages of the sample processed by the Mastersizer and the fraction retained on the 1mm sieve enabled the data to be recombined for the calculation of overall grain-size distribution statistics at a later stage. Sediment fraction data (in percent of total sample below Xμm in quarter phi increments from 2mm to 38μm) were extracted from the Malvern program, transformed into percent fraction data, the 1mm fraction was reincorporated mathematically and then the data were run through Gradistat software (Blott & Pye 2001). When new analytical techniques are introduced during long-term studies, it is essential that the results from the old and new method are comparable (Shillabeer *et al.* 1992). For beaches in the study region, it has been shown that there is a strong linear relationship between values for mean grain size and sorting derived from test-sieve and laser diffraction methods, and that a simple mathematical transformation can thus be used to adjust test-sieve values for these statistics to equivalent laser diffraction values (Ramsdale & Fairweather in prep., see Appendix 3.1). Skew and kurtosis values derived from laser diffraction analysis were not used because algorithms that smooth the grain-size distribution data in the Malvern software also alter skew and kurtosis (Blott & Pye 2006; Ramsdale & Fairweather, in prep.).

A further 5g of sediment from the core sample or sub-sample was dried (80°C for 24h) and ashed (600°C for 1h) for loss-on-ignition analysis to determine the sediment percent organic-matter content (%OM; Bale & Kenny 2005). If the amount of sand in the core sample was very small (i.e. mostly cobbles instead) then sediment samples were processed firstly for grain-size distribution statistics and %OM content analysis was only performed if there was enough (approx. 5g) dried sediment remaining, thus there were often fewer replicates in analyses of %OM content than grain-size distribution. Sediment percent moisture content (%W_a) was calculated using the wet and dry weight data from the sediment subsample processed for grain-size distribution statistics (calculated as the percentage of the mass of water of the total wet sample; Bale & Kenny 2005).

Finally, the percentage of sand and cobbles in each core was determined after drying the entire core sample (80^oC for 24h) separating the sand (defined for this study as all grains that pass through a 4mm sieve and are hence sands [or finer] according to the Udden/Wentworth grade scale; Wentworth 1922) from the cobble fraction (i.e. grains larger than 4mm in size, fitting under the broad description of gravel including granules, pebbles and cobbles, defined for the Udden/Wentworth grade scale; Wentworth 1922) and weighing each fraction. Sediment cores were not collected on the pre-summer sampling occasion of year 3 because preliminary analyses indicated little difference in sediment characteristics between beaches that was related to vehicle access or seasons.

Compaction

Three 17mL sediment samples were collected from the mid-shore at the surface for bulk density analysis. These samples were dried at 80^oC for 24h in the lab to determine bulk density (calculated as the mass of dry solids divided by the volume of the wet sample; Bale & Kenny 2005). By November 2006, a pocket penetrometer was made available for this research and from this point on 5 measurements of penetration resistance, measured in $kg.cm^{-2}$, were also taken in each zone. When there was no sand (i.e. the high shore consisted only of a cobble bank) or when there was a high percentage of cobbles mixed in with the sand it was not possible to use the pocket penetrometer. Occasionally the force required to penetrate the surface sediments was greater than that readable by the instrument (maximum $6kg.cm^{-2}$) and then penetration resistance could not be measured.

Statistical methods

All data were analysed using version 11 of the SYSTAT software package (univariate analyses) and version 6 of the PRIMER/PERMANOVA+ software package (multivariate statistics).

Data were analysed separately for each year of the study, with each 'year' containing a mid-winter, pre-summer and post-summer sampling event (Year 1: mid-winter 2005 – post-summer 2006; Year 2: mid-winter 2006 – post-summer 2007; Year 3: mid-winter 2007 – post-summer 2008). Variables measured at the level of transects (i.e. beach width, fall, slope, sand wedge area and bulk density) were compared between beaches open and closed to vehicles using a series of three (i.e. separately for each seasonal sampling occasion) 2-factor, nested, mixed-model ANOVAs with Beaches nested in Types (B(T)) as a random factor with the four study sites (Maslin, Port Willunga, Moana and Sellicks) split into two Beach levels per access Type (T) (as a fixed factor with 2 levels; Open versus Closed to vehicles).

Data for each year were analysed using three separate 3-factor nested, mixed-model ANOVAs, with the added factor of Seasonal sampling occasion (S) (a fixed factor with 3 levels; Mid-Winter, Pre-Summer and Post-Summer). For within-Bays comparisons at Aldinga and Moana, a series of three (i.e. separately for each year of the study) 2-factor, mixed-model ANOVAs, again with access Types (T) (a fixed factor with 3 levels; 3 beach sections per Bay) and three separate Seasonal sampling occasions (S) per year (a fixed factor with 3 levels; Mid-Winter, Pre-Summer and Post-Summer).

Sediment variables measured on the level of Zones (i.e. mean grain size, cobble content, %W_a, %OM content and penetration resistance) were compared between beaches open or closed to vehicles using two (i.e. separately for each year of the study) 4-factor, nested, mixed-model ANOVAs, using the above design for profile variables with the added factor of Zone (Z) (a fixed factor with 3 levels; High-, Mid- and Low-shore). Likewise, these variables were compared within-Bays as for the profile variables, using a 3-factor, mixed-model ANOVA, again with the added Zone (Z) factor. Sediment sorting values could not be normalised by transformation, and hence ANOVAs were not conducted on this variable for any comparison. ANOVA was not conducted on penetration resistance data for comparisons involving Sellicks Beach. It was not possible to record a value for penetration resistance from the cobble bed: frequently, the high-shore zone of Sellicks Beach consisted entirely of cobbles and hence there was no data for this Zone-Beach/Beach(Type) combination.

In some cases there was no sediment in samples because the entire sample consisted of cobbles (i.e. grains larger than 4mm diameter; Wentworth 1922), resulting in a number of missing samples in the analyses involving mean grain size, %W_a and %OM (Table 3.1); thus both between- and within-beach comparisons were affected by uneven sample sizes among groups (theoretical group *n* = 6 sediment samples per Zone/Beach/Seasonal sampling occasion; Table 3.1). This imbalance was minor for comparisons between-beaches and within-beaches at Aldinga Bay in the first year (i.e. only 2 samples lost from 72 or 54, respectively, for between- and within beach comparisons) and minor for within-beaches comparisons at Moana in the second year (i.e. 1 sample of 54 overall; Table 3.1).

There was severe imbalance for between- and within-beaches (Aldinga Bay) comparisons for years 2 and 3 (i.e. 5 of 6 replicate samples missing from some Beach/Zone/Season groups; Table 3.1). In addition to SYSTAT automatically accounting for minor imbalance in sampling design by using a different sums-of-squares (Type III), the degrees of freedom for the error term in affected ANOVAs were reduced and mean-squares retested using appropriate *F*-statistics; however, the results of these analyses are still interpreted with caution, especially in cases of severe imbalance. Because sediment samples were not collected during the pre-summer sampling occasion of year 3, and due to the severe imbalance in sample sizes between groups for the mid-winter and post-summer sampling occasion, ANOVAs were not conducted on sediment variables in year 3. Because comparison of the percentage of cobbles in sediment samples did not rely on the presence of sand in a core, no replicate samples have been lost from these analyses.

The presence of cobbles in sediment samples was of interest because sediments consisting of cobbles mixed with sand are considered to be poorly sorted and susceptible to compaction (Webb 1982; 1983). Differences in the occurrence of cobbles in samples from beaches with different vehicle access

Table 3.1: a) Summary table showing sediment samples missing from the analysis due to absence of sands (i.e. all cobbles with diameter >4mm; Wentworth 1922). Each Season-Beach(Type)-Zone group has a total of 6 replicates; b) summary table highlighting some factors and interaction terms with severe imbalances in sample sizes.

a)

Year	Beach	Zone	Season	Missing
1	Sellicks	High	pre-summer	1
			post-summer	1
2	Sellicks	High	mid-winter	5
			pre-summer	5
	Moana	High	pre-summer	1
3	Sellicks	High	mid-winter	4
			post-summer	4
		Low	mid-winter	1

b)

Year	Comparison	Factor	Level	Missing / total *n*
2	Between-beaches	Beach	Sellicks	10/54
		Type	Open	11/112
		Zone	High	11/72
		T*Z	Open*High	11/36
		T*Z*S	Open*High*pre-summer	11/12
	Within-beaches: Aldinga	Type	Open	10/54
		Zone	High	10/54
		T*Z	Open*High	10/18
3	Between-beaches	Beach	Sellicks	9/54
		Type	Open	9/112
		Zone	High	8/72
	Within-beaches: Aldinga	Type	Open	9/54
		Zone	High	8/54

T (between beaches = 2 levels; within bays = 3 levels) and heights Z (3 levels; high-, mid- and low-shore) for each of the nine seasonal sampling occasions were investigated using a series of contingency tables (Pearson χ^2) to investigate the question ‘are sediments on open beaches or beach sections more susceptible to compaction than closed beaches/sections?’.

In addition, multivariate statistics were used to investigate whether there were differences in the total physical environment between beaches or beach sections with different vehicle-access types. Data used were all at the level of individual transects, untransformed, and were either the actual raw measures (e.g. beach width, slope etc.) or means where duplicate (e.g. mean grain size for each zone) or replicate (e.g. bulk density measures) measurements were taken, with transects then used as replicate units (n = 3) for each beach for each season. Normalised Euclidian distance resemblance measures were used for all tests of environmental variables.

A series of permutation-based ANOVAs (PERMANOVA) was used to investigate differences in the total physical environment between and within beaches, testing the null hypothesis that there was no difference in the total physical environment between- or among-groups. According to Anderson *et al.* (2008) PERMANOVA “tests the simultaneous response of one or more variables to one or more factors in an analysis of variance (ANOVA)”. Briefly, PERMANOVA assumes that the samples are exchangeable only under a true null hypothesis, and thus is sensitive to differences in dispersion (i.e. spread around a group centroid) between- or among-groups, and thus a significant result detected by PERMANOVA may indicate a difference in centroid location or a difference in dispersion between- or among-groups (Anderson *et al.* 2008).

To separate differences in centroid location and group dispersion, PERMDISP routines (conducted on the same resemblance matrix used for PERMANOVA) were used to test for homogeneity of variances and principle coordinates (PCO) ordination plots were inspected to visually identify differences in group centroid locations (Anderson *et al.* 2008). PCO ordination plots are “a projection of data points onto axes that minimises residual variation in the space of the resemblance measure chosen” (Anderson *et al.* 2008), in this case, Euclidian distances for non-biological data. PCO plots are a better representation of the tests of dissimilarities modelled by complex PERMANOVA designs than multidimensional scaling (MDS) plots, which, like ANOSIM procedures, preserve the rank order of the inter-point dissimilarities, rather than testing the dissimilarities themselves (Anderson *et al.* 2008). PCO instead plots a projection of the points in space defined instead by the dissimilarities between points (Anderson *et al.* 2008).

PERMANOVA and PCO techniques were selected over ANOSIM and MDS to allow for the correct calculation of test statistics and better representation of patterns in the data under the complex design used in this study (Anderson *et al.* 2008). In total, two analytical designs were used, one each for the between- and within-beach comparisons, with data from each year of the study (n = 3 years; Moana Bay n = 2) analysed separately for each comparison type. Initial investigation of the data indicated that physical conditions on these beaches were highly variable among years of the study, thus the decision was made to analyse years separately to reduce the over-riding effect of this interannual variation. Data for each year were analysed using three (i.e. separately for each year) 3-factor mixed-model PERMANOVAs comparing differences in the total physical environment between Beaches nested in Types (B(T)), a random factor with the four study sites (Maslin, Port Willunga, Moana and Sellicks) split into two Beach levels per access Type (T) (a fixed factor with 2 levels; Open versus Closed to vehicles) sampled over three Seasonal sampling occasions (S) per year (a fixed factor with 3 levels; Mid-Winter, Pre-Summer and Post-Summer).

For within-beach comparisons, the nested factor (Beach) was removed from each of these designs to give a series of three (i.e. separately for each year of the study, with only 2 years for Moana Bay) 2-factor fixed-effects model PERMANOVAs investigating differences in the total physical environment among vehicle access Types (T) (a fixed-factor with 3 levels for different beach sections) and Seasonal sampling occasions (S) (a fixed factor with 3 levels; Mid-Winter, Pre-Summer and Post-Summer). MDS plots were also generated to investigate between- and within-beaches differences in the total physical environment identified by PERMANOVA.

Finally, PERMDISP was also used to investigate whether vehicle access to a beach altered the degree of variability (i.e. between samples) of the physical environment, using comparisons either between (i.e. open v. closed beaches) or among (i.e. Moana & Aldinga Bay sections) vehicle-access Types. PERMDISP was used to test the null hypothesis that there was no difference in the degree of variability in the total physical environment between- or among-groups. PERMDISP tests for the homogeneity of dispersions of samples from a group centroid (i.e. spread around a central point) and is used to check this assumption for PERMANOVA tests (i.e. as described above) but, can also be used to test hypotheses of different levels of variability among samples from two or more groups (Anderson 2006; Anderson *et al.* 2008). PERMDISP has been used here to test the hypothesis that the presence of vehicles on open beaches (i.e. between-beaches) or beach sections (i.e. within-beaches comparisons) resulted in a more variable total physical environment than that of closed beaches or beach sections.

Multivariate analyses could not be run on samples with missing values for one or more variables, and so these values had to be removed from the analyses in some way. To retain all possible replicate transects, variables were excluded where there were missing values for any year, hereafter referred to as the first method of analysis, and that used to obtain the results detailed above. This process resulted in balanced sample sizes among groups, with all replicate transects for each season/beach but, fewer variables were retained for multivariate analyses than if transects, rather than variables, were excluded due to missing values. Alternatively, transects, rather than variables, with missing values can be excluded from the analyses, unless the majority of values for that particular variable were missing, in which case the entire variable may be excluded as before. This process is hereafter referred to as the second method of analysis. When missing values were excluded in this second manner, fewer sediment grain-size distribution statistics variables are lost from the analyses but, in some cases, two or all three replicate transects were lost instead.

Due to the study design, beach sections in each Bay (i.e. within-beaches comparisons) not only represent sections based on different vehicle access Types but also sections along the length of a Bay (i.e. northern-, mid-, and southern-section), thus differences detected by ANOVA, PERMANOVA or PERMDISP, based on vehicle access Types, could also be attributed to small-scale spatial variation that can occur along the length of a Bay (for example, see James & Fairweather 1996). In an attempt to separate differences based on vehicle access Types from those due only to location of beach sections along a Bay, results from both Aldinga and Moana Bay have been compared where possible (i.e. comparisons were only possible for years 2 and 3 because Moana Bay was not sampled in year 1) because the location of different sections (i.e. based on vehicle access Types) differs between these two Bays (i.e. see Figure 1.3).

3. Results

In total, 219 transects were surveyed and 1122 sediment cores processed across the nine study beaches over 3 years. All transect variables were successfully measured on each transect. Of the sediment cores, 28 consisted entirely of cobbles (i.e. grains larger than 4mm diameter; Wentworth 1922), 27 of these came from high-shore samples at Aldinga Bay, with four each at Silver Sands and Aldinga Bollards and 19 at Sellicks, with the remaining sample coming from the high-shore zone at Moana (Table 3.1). Both Moana and Sellicks Beaches have a prominent cobble bed forming the high shore, which occasionally was the only section of beach with dry sediments (and hence defined as high-shore by this study). This occurred more frequently during winter months, with 15 of the 28 all-cobble samples collected during mid-winter sampling occasions. There was no sand for these 28 samples, and thus these samples are missing from analyses of sediment statistics (i.e. mean grain size, %W_a and %OM content).

Beach profiles

The width, fall, slope and area of beaches either open (i.e. Moana & Sellicks) or closed (i.e. Maslin & Port Willunga) to vehicles varied greatly, frequently with either significant small-scale spatial (i.e. among B(T) groups) or temporal variation (i.e. among S groups), and interaction (i.e. B(T)*S) or a combination of these (i.e. both B(T) and S significant but not B(T)*S) across the three years of the study, but no trends based on vehicle access (i.e. factor ‘T’; Table 3.2). Although small-scale spatial or temporal variation (or both) were frequently significant across more than one year of the study for most profile variables, there was no consistent patterns for differences among beaches for the three sampling occasions of each year or among

Table 3.2: ANOVA summary table for between-beaches comparisons of open (Moana & Sellicks) & closed (Maslin & Port Willunga) to vehicles. Factors are indicated with capital initials (<u>T</u>ype; <u>Z</u>one; <u>S</u>eason & <u>B</u>each). Significance levels: * = p < 0.5; ** = p < 0.01; otherwise NS. Dark grey shading indicates factors not applicable for that particular test (i.e. there is no Zone factor for variables measured at transect level); light grey shading indicates that variable was not measured on that sampling occasion. Significance values are indicated with asterisk (*p* values: * < 0.05; ** < 0.01; blank = NS). All variables square-root transformed except bulk density (BD; untransformed) & penetration resistance (PR; log(x) transformed). Abbreviations: mean grain size: MGS; organic matter: OM; moisture: W_a). An example output for each of a transect and zone level nested ANOVA is given as Appendix 3.2.

Analysis:	**Transect level**															**Zone level**														
Variable:	Width (m)			Fall (m)			Slope			Area (m^2)			BD (g/cm^3)			PR (kg/cm^2)			MGS (μm)			OM (%)			W_a (%)			Cobbles (%)		
Year:	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
T																░	░	░	**		░			░			░			░
Z	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	░	░	░			░			░	**	**	░			░
S						**				*			**	*	**	░	░	░			░			░		*	░			░
TZ	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	░	░	░			░			░	*		░			░
TS													*			░	░	░			░			░			░			░
ZS	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	░	░	░			░			░			░			░
TZS	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	░	░	░			░			░		*	░			░
B(T)	**	**			*	*	**	**	*	**	*		**	**		░	░	░		**	░	**	**	░	**	**	░	**	**	░
Z B(T)	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	░	░	░	**		░		**	░			░	**	**	░
S B(T)		**	**		*						*	*				░	░	░	**		░	**		░	**		░	**	**	░
SZ B(T)	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	░	░	░	**		░			░	**		░	**	**	░

sampling occasions for the three years of the study (i.e. no consistent trends among years for beach width; Figure 3.2a). These results indicate that the profiles of the study beaches are subject to some degree of spatial and temporal variation that was unrelated to vehicle access to the individual beaches either directly (i.e. no significant differences based on T or T*S interactions) or indirectly (i.e. no trends for S*B(T) that relate to summertime peaks in vehicle usage on open beaches; see Chapter 2 Figure 2.5).

Likewise, within both Bays, there was a great deal of variation in profile variables both spatially (i.e. among T sections) and temporally (i.e. among S sampling occasions) either as an interacting term (i.e. T*S) or separately (i.e. both T and S significant, but not T*S; Tables 3.3 & 3.4). Differences among T sections for beach width, fall and area detected by ANOVA (i.e. either T or the interaction T*S significant; Tables 3.3 & 3.4) appear not to be related to vehicle presence or absence on the different sections of both Bays. These variables (i.e. beach width, height and area) varied randomly in time and space, occasionally with some spatial pattern (e.g. beach width decreasing from north to south along Aldinga Bay; Figure 3.2b, c). During the post-summer sampling occasion at Aldinga Bay, for all three years of the study, beach width appeared to decline from being widest in the northern (seasonal closure) section to narrowest in the southern (open) section (Figure 3.2b), even though vehicles are permitted on both the northern and southern sections of this Bay for the five months prior to the post-summer sampling occasion. A similar trend was observed at Moana Bay in year 2, but not year 3, of the overall study (Figure 3.2c). Beach width in other seasons appeared to vary randomly (Figure 3.2b, c). Beach slope was frequently greatest in the open section of both Bays, regardless of location of the open section along the Bay (Figure 3.3b, c), a trend that was significant as a main factor (i.e. T significant) in years one and two, and significant as part of an interaction term (T*S) in year three for Aldinga Bay and year two at Moana (Table 3.3). Comparisons of beach slope between closed (i.e. Maslin & Port Willunga) and open (i.e. Moana & Sellicks) beaches showed no trends based on vehicle access T (Table 3.2; Figure 3.3a). This implies increased beach slope may be a vehicle effect at an individual beach level rather than an artefact of coastal geomorphology acting on different sections of the Bay(s).

Table 3.3: ANOVA summary table for within-beach comparisons at Aldinga Bay. Factors are indicated with capital initials (Type; Zone & Season). Significance levels: * = p < 0.5; ** = p < 0.01; otherwise NS. Dark grey shading indicates factors not applicable for the particular test (i.e. there is no Zone factor for variables measured at transect level); light grey shading indicates that variable was not measured on that sampling occasion. Significance values are indicated with asterisk (*p* values: * < 0.05; ** < 0.01; blank = NS). All variables square-root transformed except bulk density (BD; untransformed) & penetration resistance (PR; log(x) transformed). Abbreviations: mean grain size: MGS; organic matter: OM; moisture: W_a).

Analysis:	**Transect level**															**Zone level**														
Variable:	Width (m)			Fall (m)			Slope			Area (m^2)			BD (g/cm^3)			PR (kg/cm^2)			MGS (µm)			%OM			%Wa			%COB		
Year:	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
T	**				**		**	**	**	**	*		**	**	*				**									**	**	
Z																			**	**		**	**		**	**		**	**	
S	**	**	**	**	**	**	**	**	**	**	**	*	**	**	**				**				**		**	**		**	*	
TZ																			**									**	**	
TS		**	**		**	**			**		**	**	**	**	**															
ZS																			*						**	*		**		
TZS																							*			*			**	

Table 3.4: ANOVA summary table for within-beach comparisons at Moana Bay. Factors are indicated with capital initials (Type; Zone & Season). Significance levels: * = p < 0.5; ** = p < 0.01; otherwise NS. Dark grey shading indicates factors not applicable for the particular test (i.e. there is no Zone factor for variables measured at transect level); light grey shading indicates that variable was not measured on that sampling occasion. Significance values are indicated with asterisk (*p* values: * < 0.05; ** < 0.01; blank = NS). All variables square-root transformed except bulk density (BD; untransformed) & penetration resistance (PR; log(x) transformed). Abbreviations: mean grain size: MGS; organic matter: OM; moisture: W_a).

Analysis:	**Transect level**															**Zone level**														
Variable:	Width (m)			Fall (m)			Slope			Area (m^2)			BD (g/cm^3)			PR (kg/cm^2)			MGS (µm)			%OM			%Wa			%COB		
Year:	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
T	░	**	*	░	**	*	░	**		░	**	*	░		**	░	░	***	░	**	░	░	**	░	░		░	░		░
Z	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	░	░	***	░	**	░	░	*	░	░	**	░	░		░
S	░	**	*	░	**	**	░	**		░	**	**	░	**	**	░	░	***	░	*	░	░	**	░	░	**	░	░		░
TZ	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	░	░	***	░		░	░		░	░		░	░		░
TS	░	**	**	░	*	**	░	*		░	**	**	░			░	░	***	░		░	░	**	░	░		░	░		░
ZS	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	░	░	***	░		░	░		░	░	**	░	░		░
TZS	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	░	░	***	░		░	░		░	░		░	░		░

Figure 3.2: Box plots of raw data for beach width measurements (y-axis = width in metres) a) between-beaches open (Moana & Sellicks) or closed (Maslin & Port Willunga) to vehicles; b) within-beach sections at Aldinga Bay; and c) Moana Bay with different vehicle access, for each year of sampling (*n* = 3 years). Within-beach comparisons (mid and bottom rows) show Type sections ordered from north-most to south-most section (S: Seasonal closure; B: Bollarded; O: Open; C: Closed). Bar graphs for beach fall and area are omitted because these closely resembled those shown here. Note different scale of the y-axis between comparisons a-c.

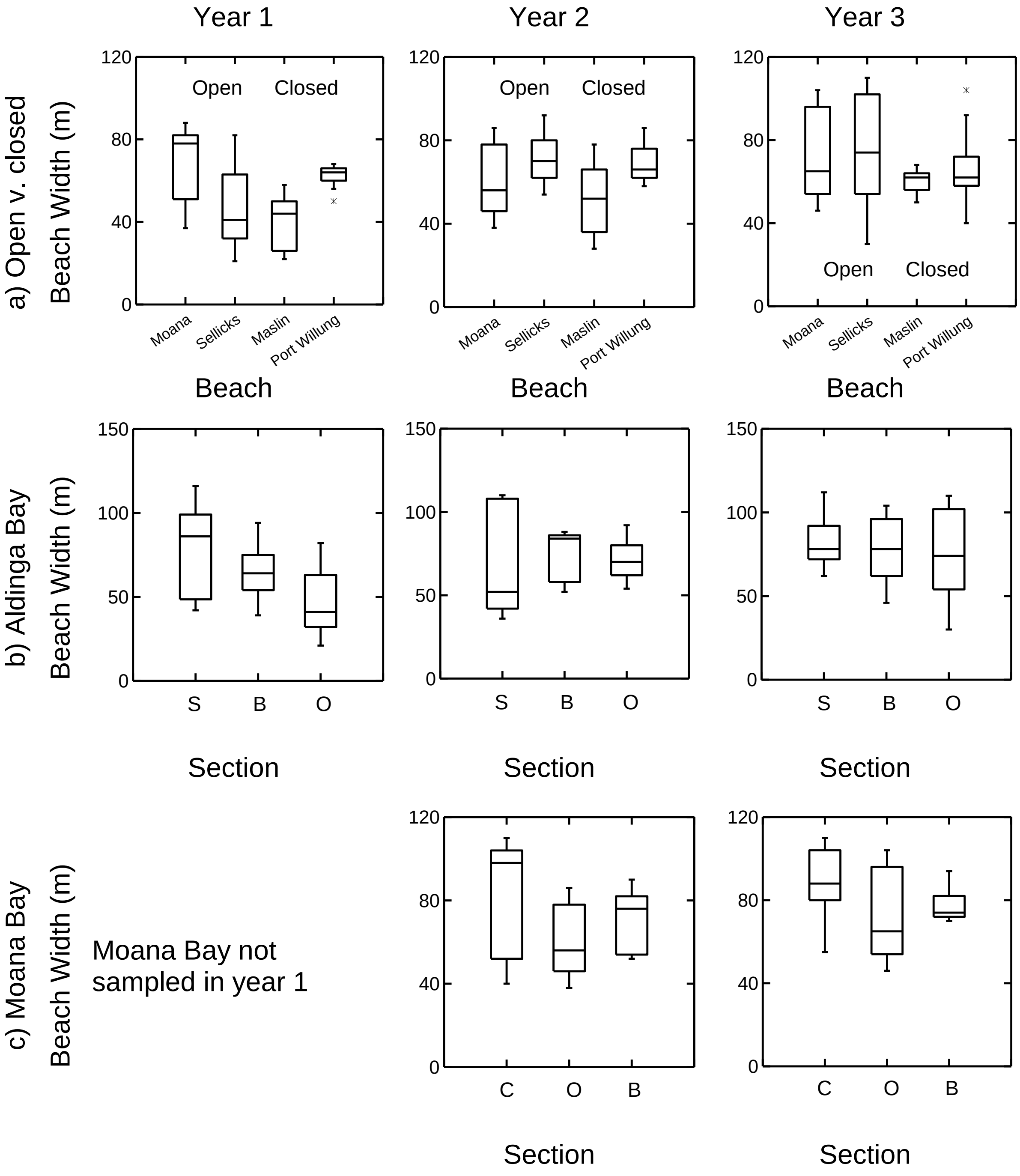
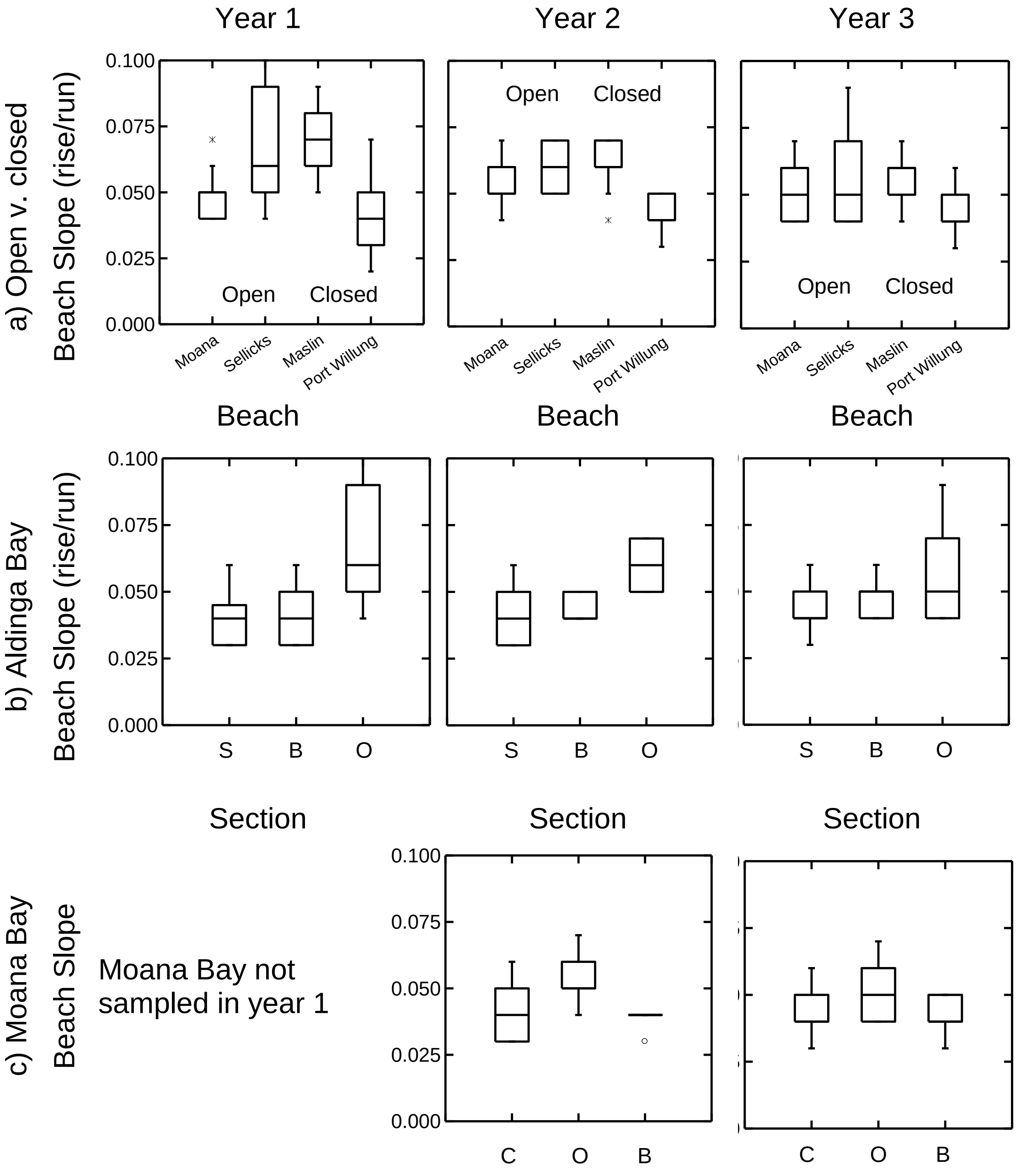


Figure 3.3: Box plots of raw data for beach slope calculations (y-axis = slope calculated as rise/run) a) between-beaches open (Moana & Sellicks) or closed (Maslin & Port Willunga) to vehicles; b) within-beach sections at Aldinga Bay; and c) Moana Bay with different vehicle access, for each year of sampling (n = 3 years). Within-beach comparisons show Type sections ordered as described in Figure 3.2. Y-axes are consistent across all nine plots.



Sediments

There was generally a positive association between the occurrence of cobbles in sediment cores on beaches open to vehicles (i.e. Moana & Sellicks) relative to closed beaches (i.e. Maslin & Port Willunga; Table 3.5a). This pattern was not as clear at Aldinga Bay, where higher occurrence of cobbles in sediment samples was occasionally associated with the permanent, bollarded closure section (e.g. pre-summer year 2) but, more frequently, with the open section (Table 3.5b). However, there was a lower frequency of cobble occurrence at Moana Bay, with no trends in the frequency of cobble occurrence between beach sections for any sampling occasion, season, year or overall (Table 3.5c). These results indicate that patterns observed between beach types (i.e. open v. closed beaches) may be being driven by the more cobbley beach at Aldinga, rather than being an effect alone of vehicles on the beach.

There was a high percentage of cobbles in sediment samples from Sellicks Beach high-shore zone during mid-winter of year 1 in both years 1 and 2 of the study, which resulted in a number of lost replicates for sediment variable comparisons (Table 3.1), which was detected by ANOVA as a significant S*Z*B(T) interaction ($F_{8,178} = 5.59$; $p < 0.01$; Table 3.2). This interaction term was also significant in year two ($F_{8,178} = 4.39$; $p < 0.01$; Table 3.2) of the study, but there were no significant differences between access T (Year 1: $F_{1,2} = 4.89$; $p > 0.05$; Year 2: $F_{1,2} = 0.85$; $p > 0.05$; Table 3.2), again indicating a high degree of temporal and small-scale spatial variation among beaches that was unrelated to vehicle activity on the beaches.

Between beaches that were open (i.e. Moana & Sellicks) or closed (i.e. Maslin & Port Willunga) to vehicles, there were few consistent and significant differences among B(T), S or Z or between vehicle access T (Table 3.2). Sediment sorting values ranged between 1.2-3.9 (very well to poorly sorted sediments; Blott & Pye 2001), and the mean value for sorting was the same (1.49; moderately well sorted sediments; Blott & Pye 2001) between beaches open versus those closed to vehicles. There was a tendency for finer sediments on open beaches for both years (Figure 3.4a), a trend that was significant for the first year (i.e. when imbalance was minor (see Table 3.1); Source: T; $F_{1,2} = 210.4$; $p < 0.01$; Table 3.2). In the second year, when 10 of

Table 3.5: Summary of results for cross-tabulations comparing the frequency of cores containing cobbles. In each case frequencies were tested on each sampling occasion (*n* = 9; *n* = 6 at Moana Bay) and for each year (*n* = 3; *n* = 2 at Moana Bay) and season (*n* = 3), separately. Tables show significant association of cobbles (bold values with level indicated by asterisk: *p* values: * < 0.05; ** < 0.01; *** < 0.001; blank = non-significant) with vehicle access a) between-beaches open and closed to vehicles; or, associations with various sections within-beaches at b) Aldinga; and c) Moana Bays. There were no sediment samples collected for the pre-summer sampling occasion on year 3, hence there are no data (n/d). Grey shading indicates that more than $^{1}/_{5}$ of cells were sparse (i.e. few cores containing cobbles) and computed significance values are suspect. Blank cells indicate that there was no trend for cobble occurrence with vehicle presence between- or within-beaches.

a) Open v. closed beaches across zones (detailed output: Appendix 3.3)

Season	Year 1	Year 2	Year 3	Overall
Mid-winter	+ cars	**+ cars*** **	**+ cars** **	**+ cars*** **
Pre-summer	**+ cars***	+ cars	n/d	**+ cars***
Post-summer	+ cars	+ cars	+ cars	+ cars
Overall	**+ cars** **	**+ cars** **	**+ cars** **	**+ cars*** **

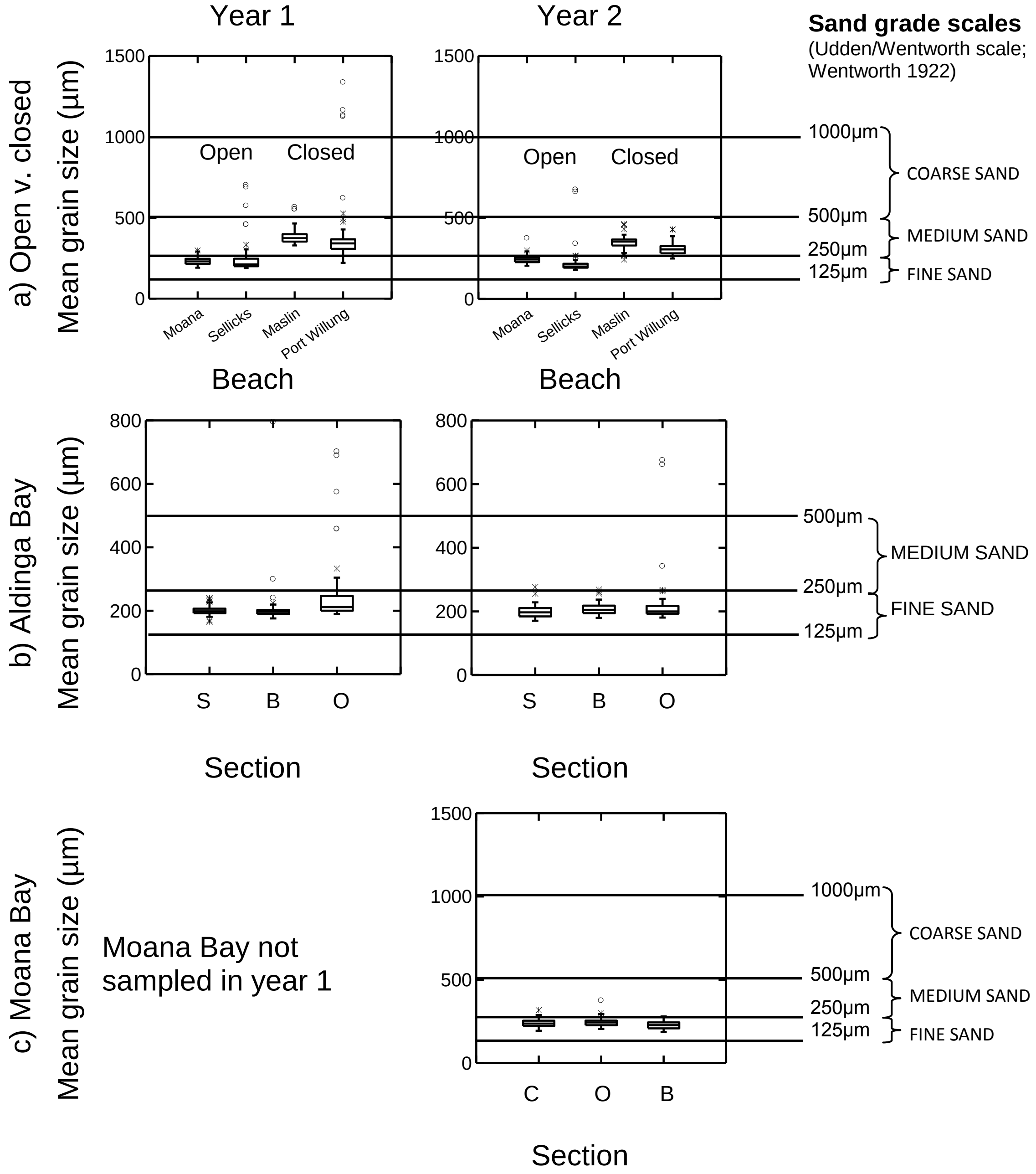
b) Aldinga Bay beach sections across zones (detailed output: Appendix 3.4)

Season	Year 1	Year 2	Year 3	Overall
Mid-winter	**+ open***	**+ cars** **	- open	+ open
Pre-summer	+ seasonal	**+ bollarded** **	n/d	**+ bollarded***
Post-summer	**+ open***	+ open	+ open	**+ open** **
Overall	**+ open** **	**+ open*** **	**+ bollarded**	**+ open*** **

c) Moana Bay beach sections across zones (detailed output: Appendix 3.5)

Season	Year 2	Year 3	Overall
Mid-winter			
Pre-summer	▨	n/d	▨
Post-summer			▨
Overall	▨		

Figure 3.4: Box plots of raw data for mean grain size (y-axis = MGS in µm) a) between-beaches open (Moana & Sellicks) or closed (Maslin & Port Willunga) to vehicles; b) within-beach sections at Aldinga Bay; and c) Moana Bay with different vehicle access, for each year of sampling (*n* = 2 years). Within-beach comparisons show Type sections ordered as described in Figure 3.2. Note different scale of the y-axis between comparisons a-c.

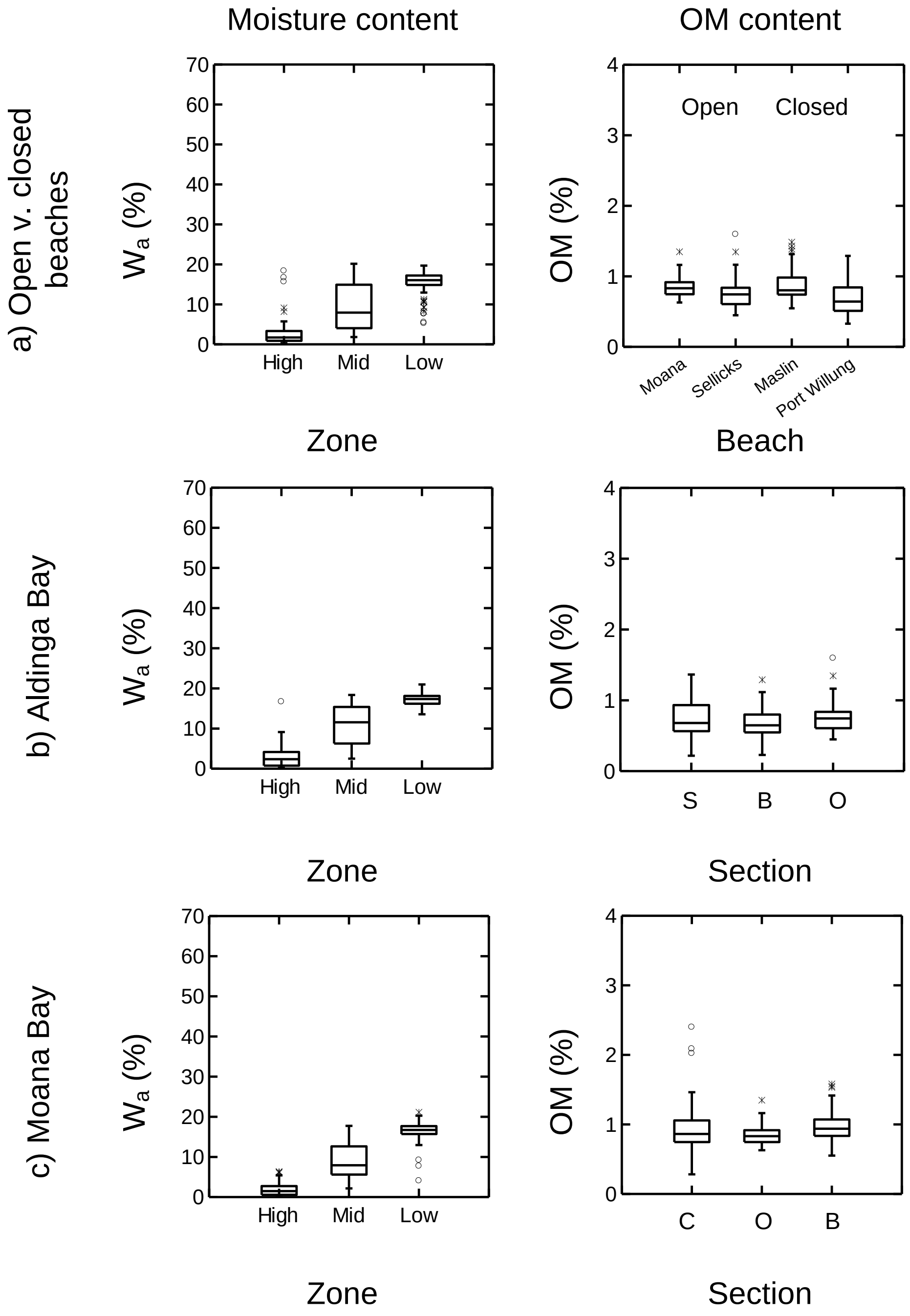


12 Sellicks Beach high-shore samples were lost (Table 3.1) and imbalance was severe only small-scale spatial differences were significant (i.e. Source: B(T); $F_{2,120} = 11.22$; $p < 0.01$; Table 3.2). In the first year, there was also a significant S*Z*B(T) interaction ($F_{8,120} = 3.64$; $p < 0.05$; Table 3.2). These results suggest that although there were patterns in mean grain size based on vehicle access, there were also strong S (i.e. temporal) and Z effects (as may be expected based on known seasonal shifts in beach morphology; McLachlan & Brown 2006) and natural variation among the individual beaches (i.e. B(T)) that overrode any effect of vehicles.

Other sediment variables showed no consistent trends based on vehicle access Types, only small-scale spatial and/or temporal variation (Table 3.2). Percent OM content differed among B(T) groups with interacting temporal effects (i.e. significant S*B(T) interaction) in the first year (Table 3.2). There were significant Z*B(T) interaction effects for %OM in the second year of the study (Table 3.2); however, due to the severe imbalance in sample size, especially for Sellicks Beach high-shore zone (Table 3.1), this result must be viewed with some caution. There was an across-shore moisture gradient from dryer sands in the high-shore zone and moister sands in the low shore (Figure 3.5a), supporting judgements used to divide the beach into these zones in the field. Differences among Z groups were detected as part of a significant interaction term of S*Z*B(T), incorporating some small-scale spatial and temporal variation among Zones, in the first year of the study. Due to the loss of five-out-of-six sediment samples from Sellicks Beach high-shore for two of three S sampling occasions (Table 3.1), the significant interaction among T*Z*S groups for $\%W_a$ content for the second year of the study (Table 3.2) cannot reasonably be attributed, even in part, to vehicle presence on open beaches.

At both Aldinga and Moana Bays there were no clear trends in sediment variables among beach sections with different vehicle access Types, and no consistent patterns between the two years of sampling at Aldinga Bay (Tables 3.3 & 3.4). Sediment sorting values ranged from 1.2-3.9 (very well to poorly sorted; Blott & Pye 2001) at Aldinga Bay and 1.2-1.9 (very well to moderately sorted; Blott & Pye 2001) at Moana Bay. Across sections, sediments all fell into the moderately well sorted range (i.e. between 1.41-

Figure 3.5: Box plots of raw data for percent moisture (%W_a, by zones: high-, mid- and low-shore, with all beaches/beach sections combined; column 1) and percent organic matter content (%OM by beaches/beach sections ordered as described for Figure 3.2; column 2) a) between-beaches open (Moana & Sellicks) or closed (Maslin & Port Willunga) to vehicles; b) within-beach sections at Aldinga Bay; and c) Moana Bay with different vehicle access, for the third year of sampling only. Within-beach comparisons show Type sections ordered as described in Figure 3.2. Note different scale of the y-axis between comparisons a-c.



1.62; Blott & Pye 2001) at Aldinga and well sorted (i.e. between 1.27-1.41; Blott & Pye 2001) at Moana. Although there were significant differences among a number of main factors (e.g. for MGS at Aldinga Bay; T and Z, for years 1 and 2, respectively; Table 3.3) and/or interaction terms (e.g. for %OM at Moana Bay; T*S for year 2; Table 3.4) the ranges of values for these variables were small for both Bays (e.g. for MGS all class as fine sands with diameter 125-250µm; Wentworth 1922; Figure 3.4b, c), and significant differences detected by ANOVA are not likely to be biologically significant. Again there was an across-shore (i.e. among Zones) gradient in moisture content at both Bays, with moister low-shore sediments and dryer high-shore sediments (Figure 3.5b, c), as expected based on the sampling protocol.

At Aldinga Bay, there were significant Z*S differences (Year 1: $F_{2,117} = 5.13$; $p < 0.01$) and Z*S*T differences (Year 2: $F_{8,117} = 2.96$; $p < 0.01$; Table 3.3), but there were no significant differences in cobble content among any factor or combination of factors at Moana Bay (Table 3.4). Cobbles were only found in five samples from Moana Bay, all during the pre-summer sampling occasion, two from the open section and three from the northern closure section (Table 3.1). One of these samples, from the high-shore zone in the open section, had a high percentage (97.7%) of cobbles while the remaining four samples had less than 1% cobble content. ANOVA detected the high-percentage cobble sample as an outlier during analysis, and removal of this sample did change some factors and interaction terms to significant but, subsequently made the remaining four samples containing cobbles outliers also. Obviously, if these outliers are also removed, there is no difference in the cobble content of sediment among beach sections at Moana, because only samples containing no cobbles would be left.

Compaction

Sediment compaction (both bulk density and penetration resistance) was similar among beaches open or closed to vehicles (Figure 3.6a). There were strong temporal effects (i.e. S significant as either a main factor or interaction term) for sediment bulk density detected by ANOVA for all years and comparisons (Table 3.2). Across the three years of the study, bulk density was higher on open beaches in mid-winter relative to closed beaches and other seasonal sampling occasions (Figure 3.7); however, this effect was

Figure 3.6: Box plots of raw data for compaction measures with bulk density (BD in g.mL^{-1}; column 1) and penetration resistance (PR in kg.cm^{-2}; column 2); a) between-beaches open (Moana & Sellicks) or closed (Maslin & Port Willunga) to vehicles; b) within-beach sections at Aldinga Bay; and c) Moana Bay with different vehicle access, for the third year of sampling only. Within-beach comparisons show Type sections ordered as described in Figure 3.2.

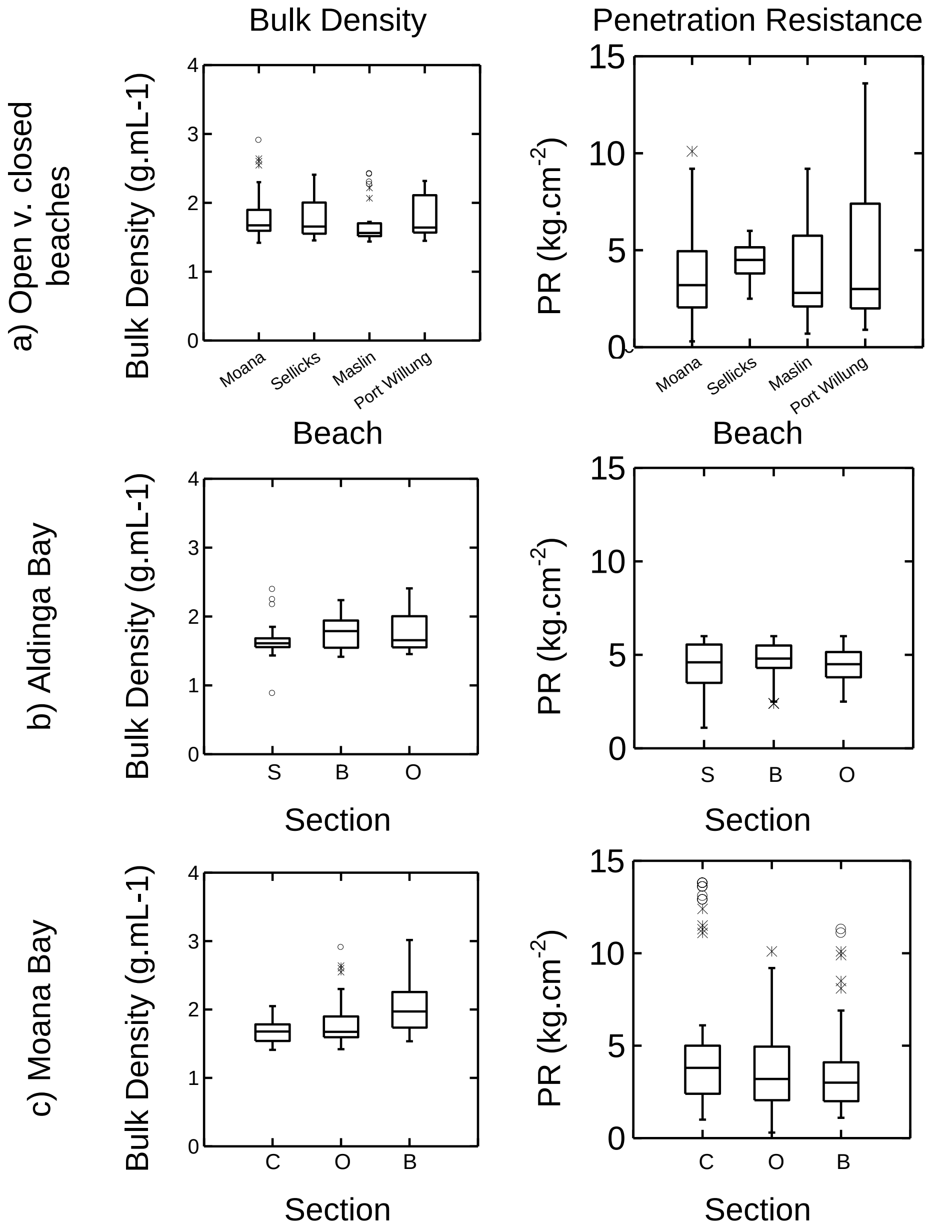
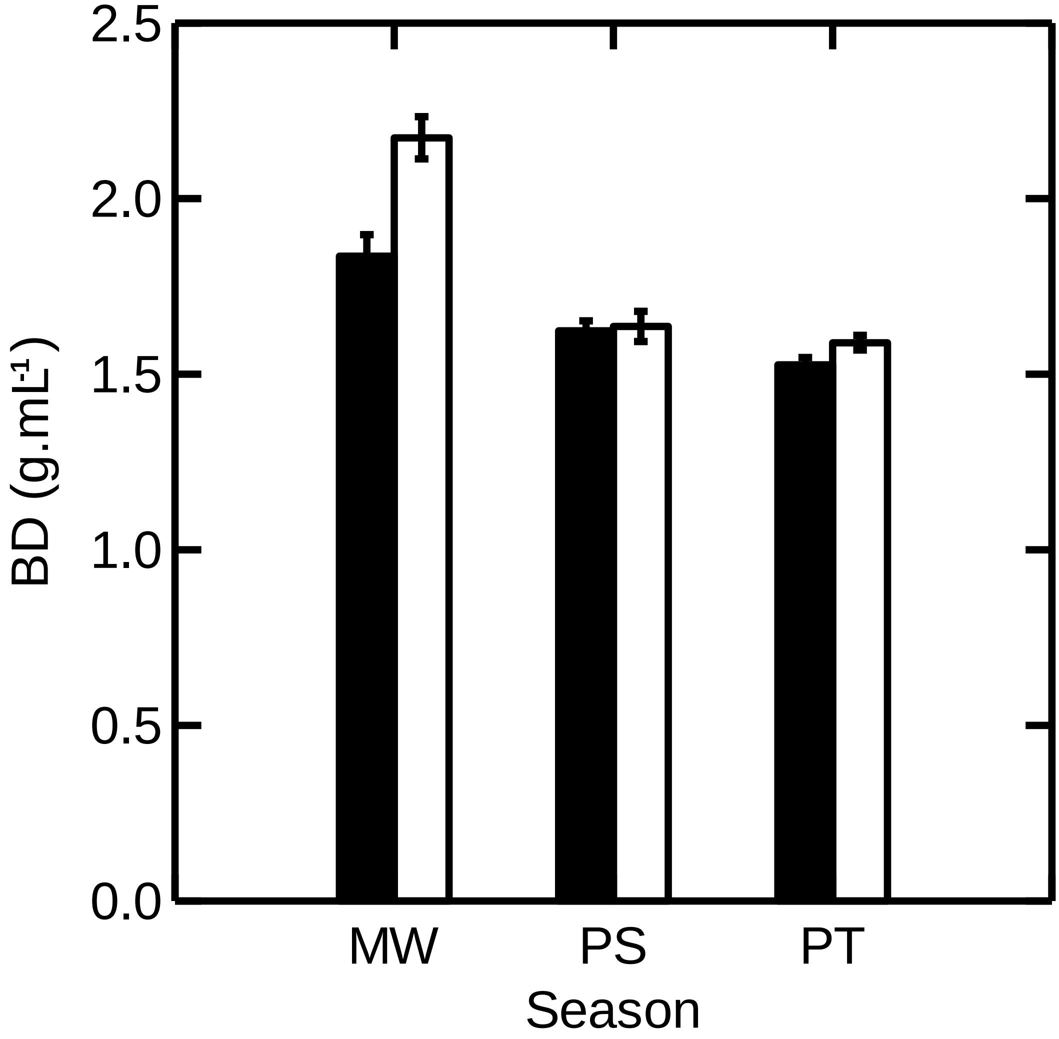


Figure 3.7: Mean bulk density (across three years of sampling; bars indicate ±SE) for closed (solid-fill bars) versus open (unfilled bars) beaches among seasons (MW: mid-winter; PS: pre-summer; PT: post-summer).



only significant during the mid-winter sampling occasion of year 1 (Source: T*S; $F_{2, 4} = 12.91$; $p < 0.05$; Table 3.2).

Sediment compaction (both bulk density and penetration resistance) was also similar among different sections of beaches within both Aldinga (Figure 3.6b) and Moana Bays (Figure 3.6c). Again there were strong temporal (i.e. seasonal) effects. Within-beaches, T effects were strongest at Aldinga Bay, with a significant T*S interaction for bulk density for each year of the study (Table 3.3). At Moana Bay, significant differences among T groups were only observed for bulk density in year 3, and only as part of an interaction term for both bulk density (i.e. T*S) and penetration resistance (i.e. T*S*Z; Table 3.4).

Physical environment

PERMANOVA tests between-beaches either open (i.e. Moana & Sellicks) or closed (i.e. Maslin & Port Willunga) to vehicles showed that there was a significant interaction effect of B(T) and S that was consistent for all three years of the study (Year 1: Pseudo-$F_{4, 24} = 3.30$; $p < 0.001$; Year 2: Pseudo-$F_{4, 24} = 1.81$; $p < 0.05$; Year 3: Pseudo-$F_{4, 24} = 3.64$; $p < 0.001$; Table 3.6a). These results indicate inherent differences in the physical environment of the four individual beaches with additional variation among S sampling occasions for each beach, overriding any effect of vehicles (i.e. T not significant as either a main factor or an interaction term). This can be seen clearly in principle coordinates (PCO) plots for each year (Figure 3.8), with replicate transects from each beach and sampling occasion generally grouping apart. These plots also show some underlying separation of transects based on vehicle access T, with transects from closed (solid-fill) and open (no-fill) beaches slightly off-set from each other (Figure 3.8) but these trends for differences in the total physical environment of the beach based on vehicle access T were never significant (Table 3.6a). However, the combined variance explained by these two-dimensional PCO plots is quite low (i.e. maximum combined total variance explained = 70.04% for year 3; Figure 3.8), generally below the recommended rule of thumb of 70% for a good representation of patterns in the data (Anderson *et al.* 2008). PERMDISP analysis of these data showed that in the first year of comparisons, there was a significantly greater degree of variability among transects from Sellicks Beach than Maslin or Moana Beaches ($F_{3, 32} = 4.21$; $p = 0.03$; Table 3.6b;

Table 3.6: Summary tables of multivariate comparisons (using those variables listed in part c); a) testing differences in the total physical environment (PERMANOVA); and b) differences in variability (PERMDISP) between- and within-beaches separately for each year of the study (significance values are indicated with asterisk (*p* values: * < 0.05; ** < 0.01; *** < 0.001; blank = NS; grey shading indicates that that factor was not applicable; e.g. there is no nested Beach term for tests within Bays). Part c) lists the physical variables available, showing those included (✓) in the analyses (blank cell = excluded; grey shading indicates variables retained if only transects with missing values are excluded [Table 3.7]; see text for explanation).

a) PERMANOVA

	Open v Closed			Aldinga Bay			Moana Bay		
Source	1	2	3	1	2	3	1	2	3
Type (T)				***	***	**	▨	**	***
Season (S)		***	**	***	***	***	▨	***	***
Beach(Type) (B(T))	***	***	***	▨	▨	▨	▨	▨	▨
S*T				*	***	***	▨		***
B(T)*S	***	*	***	▨	▨	▨	▨	▨	▨

b) PERMDISP

	Open v Closed			Aldinga Bay			Moana Bay		
Source	1	2	3	1	2	3	1	2	3
Type (T)							▨		
Season (S)	*		*				▨		
Beach(Type) (B(T))	*			▨	▨	▨	▨	▨	▨

Table 3.6: cont.

c) Variables included

		Open v Closed			Aldinga Bay			Moana Bay		
Variable		1	2	3	1	2	3	1	2	3
Width		✓	✓	✓	✓	✓	✓		✓	✓
Fall		✓	✓	✓	✓	✓	✓		✓	✓
Slope		✓	✓	✓	✓	✓	✓		✓	✓
Area		✓	✓	✓	✓	✓	✓		✓	✓
Transition	High-Mid		✓	✓		✓	✓		✓	✓
	Mid-Low		✓	✓		✓	✓		✓	✓
High-shore -	Width		✓	✓		✓	✓		✓	✓
	MGS	✓	▨	▨	✓	▨	▨		✓	▨
	Sorting	✓	▨	▨	✓	▨	▨		✓	▨
	%OM	×	▨			▨			✓	
	%Moist	✓	▨	▨	✓	▨	▨		✓	▨
	%Cobbles	✓	✓	▨	✓	✓	▨		✓	▨
Mid-shore -	Width	×	✓	✓		✓	✓		✓	✓
	MGS	✓	✓	▨	✓	✓	▨		✓	▨
	Sorting	✓	✓	▨	✓	✓	▨		✓	▨
	%OM	✓	✓		✓	✓			✓	
	%Moist	✓	✓	▨	✓	✓	▨		✓	▨
	%Cobbles	✓	✓	▨	✓	✓	▨			▨
Low-shore -	Width	×	✓	✓		✓	✓		✓	✓
	MGS	✓	✓	▨	✓	✓	▨		✓	▨
	Sorting	✓	✓	▨	✓	✓	▨		✓	▨
	%OM	✓	✓		✓	✓			✓	
	%Moist	✓	✓	▨	✓	✓	▨		✓	▨
	%Cobbles	✓	✓	▨	✓	✓	▨		✓	▨
Bulk Density		✓	✓	✓	✓	✓			✓	✓
Penetration Resistance				▨			▨			✓

Table 3.7: Number of transects remaining after exclusion of missing samples a) per beach (grouped by vehicle-access Types) between beaches open or closed to vehicles; and per Type for b) Aldinga; and c) Moana Bays, for each Seasonal sampling occasion (mid-winter: MW; pre-summer: PS; post-summer: PT) and year of the study.

a) Open v Closed beaches

			Season			
Year	Type	Beach	MW	PS	PT	Total
Year 1	Open	Moana	3	3	3	9
		Sellicks	1	3	3	7
		Total	4	6	6	16
	Closed	Maslin	3	3	3	9
		Port Willunga	3	3	3	9
		Total	6	6	6	18
	Total		10	12	12	34
Year 2	Open	Moana	3	3	3	9
		Sellicks	1	1	3	5
		Total	4	4	6	14
	Closed	Maslin	3	3	3	9
		Port Willunga	3	3	3	9
		Total	6	6	6	18
	Total	Total	10	10	12	32
Year 3	Open	Moana	3	0	3	6
		Sellicks	2	0	0	2
		Total	5	0	3	8
	Closed	Maslin	3	0	3	6
		Port Willunga	3	0	3	6
		Total	6	0	6	12
	Total	Total	11	0	9	20

b) Aldinga Bay

		Season			
Year	Type	MW	PS	PT	Total
Year 1	Seasonal	2	3	3	8
	Bollarded	1	3	3	7
	Open	1	3	3	7
	Total	4	9	9	22
Year 2	Seasonal	3	3	3	9
	Bollarded	3	3	3	9
	Open	0	1	2	3
	Total	6	7	8	21
Year 3	Seasonal	3	0	3	6
	Bollarded	3	0	3	6
	Open	2	0	0	2
	Total	8	0	6	14

Table 3.7: cont.

c) Moana Bay

		Season			
Year	Type	MW	PS	PT	Total
Year 2	Seasonal	3	3	3	9
	Bollarded	3	3	3	9
	Open	3	3	3	9
	Total	9	9	9	27
Year 3	Seasonal	3	0	3	6
	Bollarded	3	0	3	6
	Open	3	0	3	6
	Total	9	0	9	18

Figure 3.8: Principle coordinates (PCO) analysis ordination plots of the total physical environment for transects from beaches open and closed to vehicles for each year of the study. The two columns show the same PCO plot for each year. The first column shows groupings based on the significant interaction effect of B(T) (Moana: striped-fill; Sellicks: no-fill: Maslin: solid-fill; Port Willunga: grey-fill) and S (indicated by point shape: circles: mid-winter; squares: pre-summer; triangles: post-summer) that was detected by PERMANOVA for each year (Table 3.6a); the second column highlights the separation of transects by vehicle access T (closed: solid-fill; open: no fill).

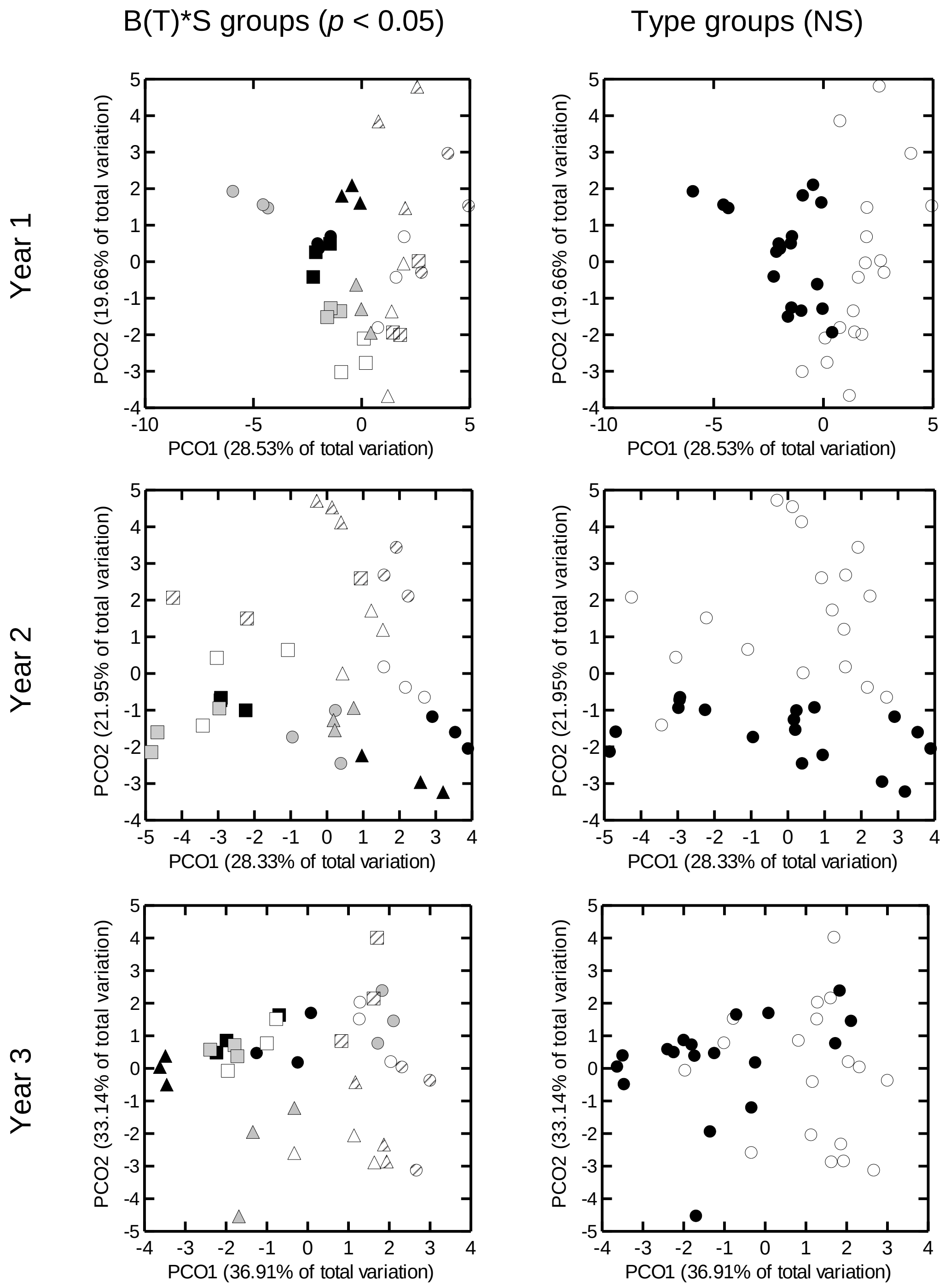
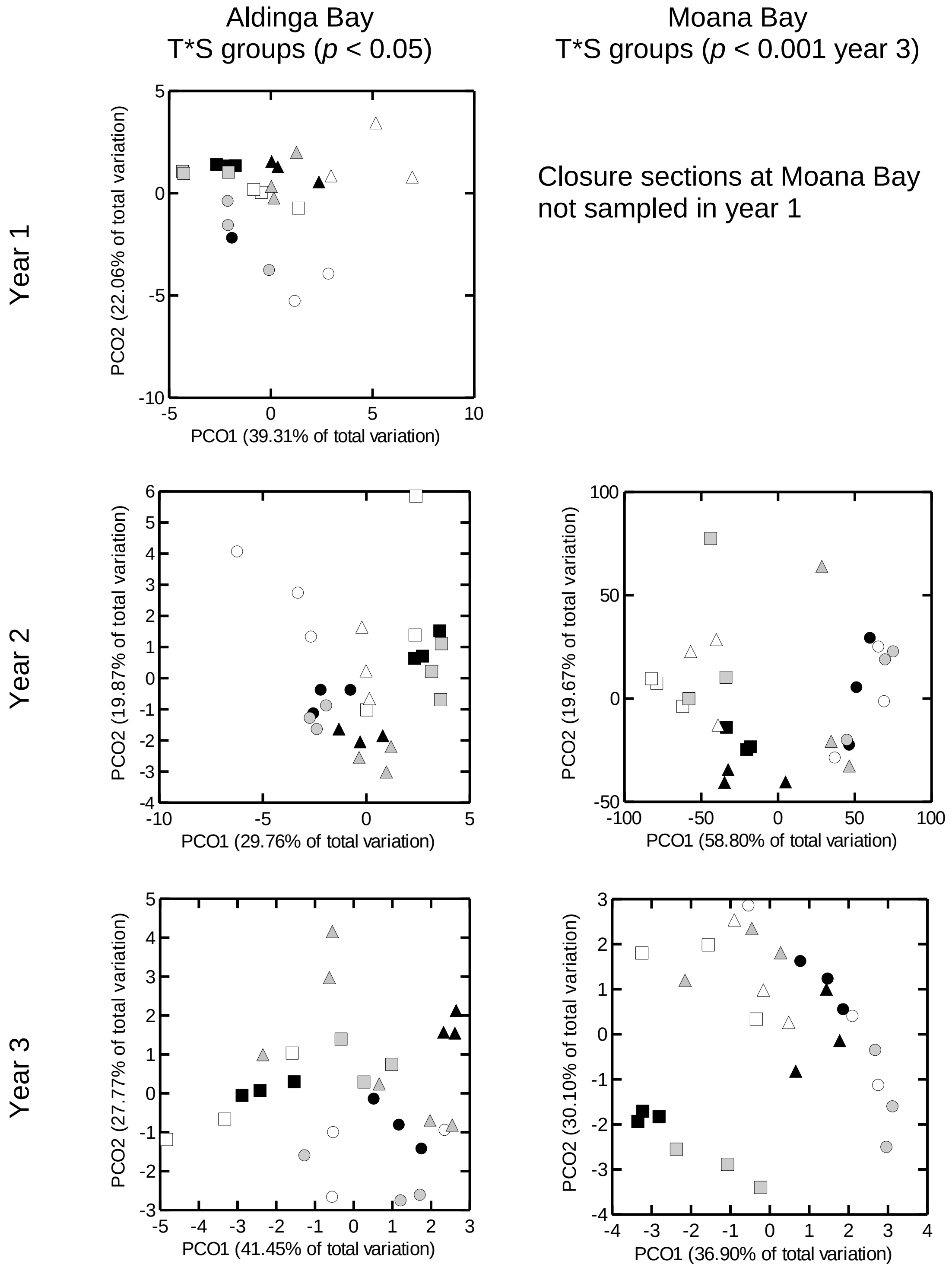


Figure 3.8). There was also lower variability among replicate transects measured during the post-summer sampling occasion relative to transects from other seasons in year 1 that were not detected by PERMANOVA ($F_{2, 33} = 5.98$; $p < 0.05$; Table 3.6a, b; Figure 3.8), and significantly higher variability among replicate transects during the pre-summer sampling occasion of year 3 ($F_{2, 33} = 5.48$; $p < 0.05$; Table 3.6b; Figure 3.8). Differences in variability of the total physical environment of the beach were not consistent for seasonal sampling occasions among years of the study.

There were significant Season*Type interaction terms for all three years of sampling at Aldinga Bay detected by PERMANOVA (Year 1: Pseudo-$F_{4, 15} = 2.08$; $p < 0.05$; Year 2: Pseudo-$F_{4, 18} = 3.24$; $p < 0.001$; Year 3: Pseudo-$F_{1, 18} = 4.39$; $p < 0.001$; Table 3.6a) but only for year 3 at Moana (Pseudo-$F_{4, 18} = 3.76$; $p < 0.001$; Table 3.6a), although each of T and S was still significant at Moana in year 2, even though the interaction term was not (Table 3.6a). PCO plots for both Bays showed no clear trends based solely on vehicle access among the three beach sections (i.e. closed sections do not group away from open ones), but instead groupings based on the three seasonal sampling occasions were apparent in both Bays for all years of sampling (Figure 3.9). Although the percentage of total variance explained by the two-dimensional PCO plots (Figure 3.9) for both Bays was higher than that for comparisons between-beaches (Figure 3.8), again these plots are not likely to represent accurately the patterns in the data (Anderson *et al.* 2008). PERMDISP detected no trends for increased variability in the physical environment either between beaches that were open or closed to vehicles or among sections of beaches within Bays with different vehicle access types detected by PERMDISP analysis (Table 3.6b), indicating that differences detected by PERMANOVA were due to shifts in the total physical environment (i.e. changes among seasons) rather than changes in variability.

When data were analysed using the second method of analysis, differences between-beaches, based on vehicle access Types, that were apparent in PCO plots (Figure 3.8) but not significant when data are analysed using the first method of analysis (Table 3.6a), become significant for years 1 (Pseudo-$F_{1, 2.01} = 2.67$; $p < 0.001$) and 2 (Pseudo-$F_{2, 2.05} = 1.75$; $p < 0.001$) of the overall study. Also, significant differences among seasons between-

Figure 3.9: PCO ordination plots of the total physical environment for transects from within-bay comparisons for each year of the study. The two columns show PCO ordination plots for Aldinga (right) and Moana Bays (left) with groupings based on the significant interaction effect of T (open sections: no-fill; bollarded closures: solid-fill; seasonal closure [Aldinga]: grey fill: closed section [Moana]: grey fill) and S (based on point shapes as per Figure 3.8) detected by PERMANOVA (Table 3.6a) for each year.



beaches in year 3 detected by the first method of analysis (Table 3.6a) became non-significant when individual transects, rather than variables, were excluded. Otherwise, there were no major changes, specifically significant results becoming non-significant, or vice versa, for between- or within-beaches comparisons for any year of the study, even though the loss of replicate transects does reduce the degrees of freedom in these analyses. SIMPER analysis to determine which variables contributed highly to dissimilarity in the total physical environment between beaches that were open versus closed to vehicles showed that sediment variables in both years 1 (mid-shore % moisture & mean grain size, high-shore % cobbles) and 2 of the study (mean grain size for mid- and low-shore, high-shore % cobbles).

SIMPER analysis on data selected using the first method (NS difference between access Types) showed that the highest contributors to observed differences in the total physical environment between vehicle-access Types were sediment variables. These variables were all excluded by the first, but not the second, method of analysis in year 3 (Table 3.6c), and it may be that exclusion of these variables at least partially contributes to the change in significance level for the factor Type. In total, 16 replicate transects were lost from the data set using the second method of analysis, due to the exclusion of all transects from the pre-summer sampling occasion, as well as a number of additional transects that are lost from Sellicks Beach (Table 3.7). The second method did, however, retain the variables selected by SIMPER analysis as defining variables between closed and open beaches (Table 3.6c), but did not detect a significant difference between vehicle-access Types. Seasonal differences detected by PERMANOVA using the first method were also detected as differences in the spread amongst transects from each season by PERMDISP, with transects from the pre-summer sampling occasion significantly more widely spread than transects from other seasonal sampling occasions (Table 3.6a,b; Figure 3.8). The pre-summer sampling occasion was omitted using the second method of analysis, thus seasonal effects could not detected by PERMANOVA.

4. Discussion

There were no apparent effects of vehicles on the profile or sediment values of the study beaches, only beach slope showed any indication of being influenced by vehicle presence on the beach. However, this result was at least partially attributable to the presence of a high-shore cobble bank on the open beaches and beach sections. It is not possible to say from these data whether the prominence of the cobble banks, which are a natural feature of these beaches, is exacerbated by vehicle use of the beach. That beach slope is steeper on open beaches or beach sections (i.e. in both the between- and within-beaches comparisons) suggests that there may be an effect of vehicles on beach slope at the level of an individual beach. This effect may be missed by a straight-forward comparison of beaches of different access types. Thus, effects of vehicles may be relative to what is normal for that beach, especially in cases such as this, where there is a high degree of variability among beaches regardless of vehicle access.

Changes in the significance level of the factor Type between the two different methods of excluding missing values for multivariate analysis between-beaches are difficult to explain. Loss of replicate transects occurred only at Sellicks Beach in years 1 and 2, and all beaches in year 3 (Table 3.7) but, change in significance levels for the factor Type (i.e. from non-significant to significant) was only seen in years one and two. In year three, sediment cores were not collected from beaches during the pre-summer sampling occasion. Because of this, 16 variables were lost from the data set using the first method of analysis, 13 more variables than were lost using the second method (Table 3.6c). It is likely that both methods of analysis lose either too many replicates or variables (and also power) to detect a significant difference between vehicle-access Types in year 3 of the study. These two different methods for excluding missing samples in the multivariate analyses used in this chapter both tell us something important about differences in the total physical habitat between-beaches in the study region. The first method maximises replication within factor levels and best represents the intrinsic variability among beaches in the study region, especially natural temporal and spatial variability in the profile characteristics of these beaches (Table 3.6) but, does this at the cost of the number of variables that can be included in the analysis. The second method maximises the number of variables included in the analyses, particularly for sediment variables (Table 3.6), and detects the differences between beaches that are apparent from eyeballing the study sites (and PCO plots), that is, that open beaches tend to have firmer, finer sands relative to closed beaches. However, within-beaches comparisons suggest that these differences are not related to vehicle activities. More likely, beaches with firm, fine sands are more suitable for beach driving, and hence have been preferred by drivers. Thus, in this thesis, it has been important to consider the results of both methods of excluding missing samples when interpreting the results of these analyses.

Importantly, it has been shown in this chapter that Aldinga Bay, and especially the permanently-open section, Sellicks, has sediments that are highly susceptible to compaction by vehicles. This beach has a high percentage of cobbles mixed with otherwise fine sands, which suggests poorly sorted (i.e. bimodal) sediments. Sorting indicates the distribution of sediment grain sizes. Poorly-sorted sediments, with a wider distribution of grain sizes, show increased susceptibility to compaction, with the ratio of small to large particles and percentage of large particles present being important determinants (Webb 1982, 1983). Thus beaches with a large percentage of cobbles or gravel mixed with fine sands may be more susceptible than well-sorted coarse or fine sand beaches due to their poor sediment sorting. Unfortunately, because there is no available sediment data predating vehicle use on Aldinga Bay, it is impossible to determine if fine sands with cobbles are a natural occurrence on these beaches, a result of vehicle actions over the last ~60 years or indeed a natural feature that is exacerbated by the presence of vehicles on the beach. To make such a determination, many more cases would need to be looked at. Further, all beaches in the study region, regardless of vehicle access, have naturally-occurring high-shore cobble beds that are usually an underlying (i.e. buried) feature (Caton 2007) but only exposed at times of severe storm erosion. Thus, even though other beaches did not have as high a percentage cobble content as those in Aldinga Bay, there is still potential for susceptibility to sediment compaction on all beaches in the study region.

The results of this study suggest that small-scale spatial variation, rather than vehicle impacts, may contribute more to sediment compaction on the study beaches. Bulk density showed a tendency to increase towards the southern sections of both Bays (e.g. see Figure 3.6b,c), even though one of these sections is open to vehicles (i.e. at Aldinga Bay) and the other bollarded (i.e. at Moana Bay), suggesting small-scale spatial variation along the length of a Bay, rather than vehicle effects, may be a more important factor for sediment compaction on these beaches (i.e. T being significant in each comparison as a spatial factor rather than an effect of vehicles). This spatial effect may be exaggerated by both vehicles and poorly sorted sediments at Aldinga Bay; differences based on Type sections were stronger in Aldinga Bay, with the section permanently open to vehicles located at the southern end of the Bay.

The apparently minimal effect of vehicles on sediment compaction was surprising given the findings of similar studies that showed changes in compaction of sediments directly attributable to vehicles on intertidal sandy beaches and dune systems (Hosier & Eaton 1980; Anders & Leatherman 1987; Schlacher *et al.* 2008b; also see Chapter 4 of this thesis for a discussion of vehicle effects on sediment compaction), and the apparent susceptibility of sediments to compaction due to poor sorting, especially at Aldinga Bay (this Chapter). Where different depths in the sediment body have been investigated for compaction effects of vehicles it has been shown that vehicles cause loosening of surface sediments but compaction at depth (Hosier & Eaton 1980; Anders & Leatherman 1987). Because only surface sediments were sampled in this study, compaction effects may have been missed if increased compaction only occurred at depth; however, decreased compaction of surface sediments was not observed on open beaches relative to closed ones. Sediment bulk density increased on the study beaches during mid-winter sampling periods, with a greater increase observed on open beaches. At this time on the study beaches, deeper layers of sand are exposed at the surface due to erosion of surface sediments during wintertime storm events. It is possible that vehicles are causing compaction of sediments at depth on open beaches in the study region, an effect that was only observed when deeper layers were exposed at the surface by natural erosion during mid-winter sampling occasions.

Overwhelmingly, inconsistent and/or variable trends, in conjunction with frequently significant temporal and spatial variation for all between- and within-beaches comparisons using uni- and multivariate datasets, suggest that the physical structure of beaches in the study region are subject to a high degree of natural variability that overrides most effects of vehicles. These results suggest that the beaches in the study region exist in a highly variable state, subject to seasonal and small-scale spatial differences in physical forcing factors that most likely cause the observed physical differences among beaches. These data alone are not enough to define seasonal or spatial patterns of variation in beach profile or sediment values, or to identify patterns of change in the physical environment. However, it does seem reasonable to assume from these results that, in the face of such a high degree of natural variation, vehicles are having very little impact on the physical environment of the intertidal beaches surveyed in this study. In fact, from the results presented in this chapter, it seems that the measured variables are not sensitive to intense vehicle traffic (see Chapter 2). There is some indication that open beaches represent different total physical environments relative to closed beaches from the multivariate analysis; however, without data predating vehicle use on these beaches, it is impossible to discern whether these differences were caused by vehicles or were, in fact, pre-existing. Comparing the results of between- and within-beaches multivariate comparisons does indicate that the beaches at both Aldinga and Moana Bays are more suitable for beach driving, with finer, generally more compact sediments, and it is possible that this is why they were initially selected or preferred by drivers.

5. Conclusion

This chapter has identified that there is a high degree of small-scale spatial and temporal variation (i.e. inherent differences among beaches) in the physical structure of sediments, profiles and the total physical environment of the study beaches, frequently overriding any effects of vehicles. None of the expected outcomes from Chapter 1 (i.e. open beaches or beach sections having steeper profiles, increased compaction of sediments, altered grain sizes; see Figure 1.5) were observed. However, sediments at Aldinga Bay, in particular, have been shown to have a high susceptibility to compaction due to having a high percentage content of cobbles mixed with sands. There were no differences in sediments, profiles or the total physical environment related to vehicle impacts (i.e. between or among different beaches or beach sections), or combined with seasonal differences in vehicle usage (see Chapter 2) or zones of the beach-face.

The unique design of this study allows detection of variability in time and space that would otherwise be missed in simple comparisons between beaches based on type, making it unconfounded with small- or large-scale spatial or seasonal variation. Thus, it appears that at the level of vehicle usage on these beaches (see Chapter 2, this thesis), vehicles do not appear to be affecting beach profile or sediment characteristics, except perhaps beach slope and sediment compaction, and that, instead, natural forces (e.g. wind, waves, sediment supply etc.) appear to have a more influential effect on these particular beaches.