CHAPTER 4: SEDIMENT COMPACTION AND DISPLACEMENT ON BEACHES BY EXPERIMENTAL VEHICLE TYRES

1. Introduction

Vehicles can cause compaction, disturbance and down-slope displacement to the sediments on beaches, potentially resulting in large volumes of sediment being displaced into the swash zone and lost from the intertidal beach (Anders & Leatherman 1987). Rutting (i.e. the forming of deep tracks in the sediment) on a popular beach can be extensive (Schlacher & Morrison 2008, Schlacher & Thompson 2008). Rutting is deeper in the soft sand between the fore-dune and the drift-line, than on the moist foreshore (Anders & Leatherman 1987; Schlacher & Thompson 2008). Sediment displaced from the tyre rut forms mounds either side of the vehicle track, and where the vehicle passes on a slope, the down-slope mound is larger than the up-slope mound (Anders & Leatherman 1987). Both rutting and loss of the surficial salt-crust on high-shore sands caused by vehicles increases surface roughness, beach topography variability, and aeolian sand transport (Leatherman & Godfrey 1979), so the destruction of these surficial crusts, in conjunction with rutting or tracking of the beach and sediment down-slope displacement, together have a potentially significant impact beach sediment budgets. Erosion via the cumulative displacement of sand down-slope to the swash zone from beach-face rutting was estimated to be a net loss of up to 119,300 m^3yr^{-1} on one North American beach, and it was proposed that this amount could be reduced by as much as 81% by restricting driving to the flatter area behind the berm at the top of the beach (Anders & Leatherman 1987).

Beaches open to vehicles in the southern metropolitan Adelaide region are often severely rutted by vehicle traffic, especially during the summer months; however, the impacts of this rutting are difficult to ascertain from the literature alone because these beaches are relatively sheltered from wave action, unlike those previously studied for sediment displacement and disruption (e.g. Anders & Leatherman 1987). Beaches in the study region tend to not form a summer berm, thus remaining fairly flat and wide throughout the year (pers. obs.). Anders and Leatherman (1987) postulated that vehicle impacts on sediment movements may be reduced on flatter beaches lacking a berm, but this hypothesis remains untested. Thus, the aim of this study was to investigate changes to sediment compaction, displacement and disturbance by vehicle tyres on a beach in the southern metropolitan Adelaide region (see Chapter 1, Figure 1.5), via the experimental application of vehicular traffic.

Specifically, this chapter will:

- Compare sediment compaction, displacement and disruption due to vehicle passes among different zones on the beach (high-, mid- and low-shore);
- Determine the environmental variables that drive sediment displacement and disturbance by vehicles; and
- Estimate the potential volume of sediment displaced on the study beach based on observed vehicle usage.

2. Methods

Study site

Silver Sands Beach at Aldinga, South Australia (a 1.8km long section of Aldinga Bay; see Chapter 2; Figure 2.2), a southern metropolitan Adelaide beach open to vehicles in the austral summer months (1st Oct. – 1st May), was selected as the study site for this experiment. This beach rarely forms a summer berm, instead remaining relatively flat (average slope 2.5 degrees) and wide throughout the year. Other beaches open to vehicles in the region were not suitable for this experiment. Sellicks Beach, at the other end of Aldinga Bay (see Figure 2.2) has a high-shore cobble bed not safe for driving (although some drivers do traverse the cobble bed; see Results), and the Moana Beach high-shore was so severely rutted at both times of sampling that it was impossible to find a relatively undisturbed area in which to conduct experimental trials. Typical track densities at Silver Sands are 0.830 ±0.123 tracks.m^{-1} (n = 20 transects) across the width of the beach during summer but less in winter during the closure period (0.231 ±0.066 tracks.m^{-1}; n = 15 transects; see Chapter 2). There is one vehicle access point (ramp) to this section of beach, at the northern end of the beach, which is used by all vehicles entering and leaving the beach (see Chapter 2; Figure 2.2).

Silver Sands beach section typically displays a Low Tide Terrace (LTT) morphotype (Short 2006b), with high-shore reflective and low-shore dissipative profiles (see Appendix 1.3) and has typically fine sediments (approx. 200µm). The high-shore consists of a dry, fine sand-covered cobble bank backed by vegetated foredunes and stable, vegetated dunes with some urban development, including a sealed road. The high-shore zone has poorly sorted (i.e. sand mixed with cobbles), dry sediments that are susceptible to compaction (Webb 1982, 1983). The mid-shore has fine, moist sands also mixed with cobbles. Some compaction resistance may be expected in this zone due to partial load bearing by entrapped air in the capillary spaces, which occurs in moist but not dry or saturated sands (Webb 1982). The low shore has fine, wet sands also mixed with cobbles. Compaction susceptibility of this poorly-sorted and water-saturated zone is expected to be high (Webb 1982, 1983).

Field methods

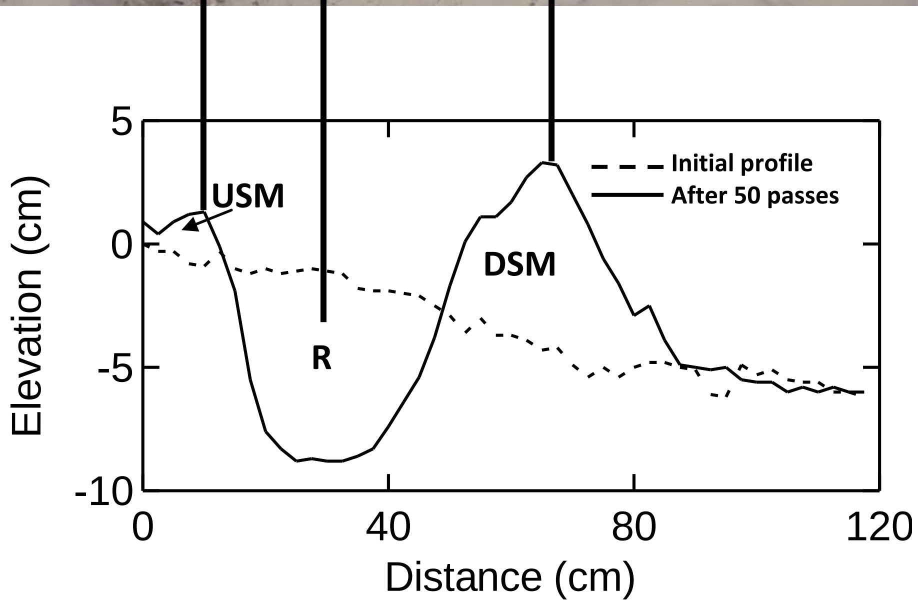
Experiments were conducted on two separate occasions (December 2007 & October 2008). These visits were timed so as to fall within the summertime open season for vehicles on the study beach but to avoid the peak vehicle usage time (Dec. – Feb. and the Easter long weekend; see Chapter 2), when the beach became too rutted (and too busy) for sampling. The beach was divided visually into three zones (high-, mid- and low-shore) based on the moisture of the sediments according to the zonation scheme proposed by McLachlan & Jaramillo (1995; see Chapter 1).

At least three replicate microtopography transects were conducted in each zone. Each transect ran across-shore, established perpendicular to the swash zone and ran for the length of the microtopography instrument (1.4m; Figure 4.1a). This instrument was constructed based on the microtopography profiler (MTP) designed and described by Leatherman (1987). The instrument constructed for the current experiment consisted of a pine stand (similar in appearance to a saw-horse) with adjustable legs to allow for levelling of the instrument. The stand supported a double-frame (the double-frame improved pole straightness) for holding 49 individual 9mm diameter doweling poles, each held in place with a rubber washer (poles could thus be

Figure 4.1: a) Photograph showing the microtopography instrument in use in the high-shore zone. The instrument was levelled before measurements using a spirit level (not pictured). For scale, each vertical measurement pole in the frame is 75cm in length; b) Example profile plot from high-shore transect 3 showing the single rut form the initial and 50 passes beach topography. The plot shows a clear rut (R), up-shore (USM) and (bigger) down-shore (DSM) sediment mounds, corresponding to features seen in part a (note: this is a representation only, data in the plot do not correspond to the photographed profile).

a)

b)



gently lowered by hand to the sediment surface). Poles were placed in a straight line and spaced exactly 2.5cm apart (see Figure 4.1a). This instrument allowed the measurement of the 2D surface topography down to 1mm changes in profile height. The accuracy of the microtopographer was tested by repeatedly measuring, removing and replacing the instrument on each transect without applying vehicle traffic. By this method, the instrument was found to be accurate to within 1.7mm on average (n = 8 transects tested).The vehicle selected for the experimental trials was a Toyota Rav4, an all-wheel-drive, on-road vehicle, typical of vehicles used on the southern Adelaide metropolitan beaches (pers. obs.) and capable of traversing the soft high-shore area. Vehicle weight (gross vehicle mass = 2100 kg), tyre pressures (30 psi, typical of the vehicles driven on this beach), width (tyre width = 18cm) and vehicle speed (10km/h, the official beach speed limit) were kept constant during trials with no acceleration or breaking while the vehicle was passing though the experimental transect.

Transects were established in haphazardly-selected sites in the middle of randomly-selected zones in areas that had no visual recent disturbance by vehicles (specifically no tracks or ruts seen), although prior disturbance of the area can be assumed. Five measures of surface penetration resistance (hereafter PR) were taken using a Geotester pocket penetrometer from the centre of the transect and an initial surface sediment sample (for mean grain size [hereafter MGS], sorting and moisture content analysis) was collected from the centre of the transect using a 60mL corer (diameter 3cm to 8.5cm depth). Sediment samples were processed in the laboratory using standard weighing and drying methods, MGS and sorting were obtained by laser diffraction analysis (for sample processing details see Chapter 3).

The initial topography and slope of the transect was recorded using the microtopographer, then the instrument was moved and the vehicle driven though the transect once (1 vehicle ‘pass’), creating a track. The track was always straight, as close to the centre of the transect as possible and ran parallel of the swash and perpendicular to the beach slope. Following the vehicle pass, the microtopographer was returned to its original location on the transect, now with one vehicle track passing through it, and the topography of the beach-face remeasured. The position and width of the track was also recorded. Five PR measurements were taken from the centre of the track, and another five measures from haphazardly-sampled areas either above or below the track, randomly chosen. It was desired to compare the compaction of sediments inside the vehicle track (i.e. the area directly subjected to vehicle traffic) to nearby (i.e. within a metre) undisturbed sediments. However, there was only limited ‘undisturbed’ sediment in the area around the track, and it was not possible to sample both above and below the track after every set of passes, hence the decision was made to sample randomly both above and below (defined hereafter as ‘outside’ the track) to determine the compaction of the sediments around the track relative to within it (defined as ‘inside’). This process was then repeated after a further 2 passes along the same track in the same rut (then total = 3 passes) then at 5, 10, 15, 20, 25, 30, 40, 50 and 75 passes (*sensu* Anders & Leatherman 1987). As well as these regular measurements taken after each set of passes, upon completion of all vehicle passes a second sediment sample for MGS, sorting and moisture content analysis was collected.

As the vehicle passed through the transect each wheel created a rut into the sand and a mound of sediment on either side of the rut, the larger of which being down-slope of the rut (Fig. 3.1b). On completion of the field trials, microtopography plots were used to measure the cross-sectional area of the rut (R), up-slope mound (USM) and down-slope mound (DSM) after each set of passes, by measuring the deviation of the topography from the original un-rutted state (Fig. 3.1b). These measurements could then be used to calculate net down-slope movement (NDSM = DSM – USM) and net disruption (NDR = R - (DSM + USM)), using equations from Anders & Leatherman (1987).

Statistical methods

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

To determine which environmental co-variables and/or experimental factors (measured variables; initial sediment mean grain size, sorting, % sediments greater than 1mm diameter and moisture content, surface strength (PR), beach slope; as well as number of vehicle passes and track width) were driving observed sediment displacement (measured net down-slope displacement and net disruption), a multivariate BEST (BIO-ENV) analysis was used. This analysis searches for high rank correlations between a fixed sample similarity matrix (in this case, sediment displacement measures) and a second matrix of normalised environmental variables, presumed to contain those driving any patterns observed in the first matrix (Clarke & Gorley 2006). The global BEST match permutations test (999 permutations) was used to test the significance level of the Rho (Spearman correlation coefficient) sample statistic generated by the BIOENV analysis.

A series (i.e. separately for each zone) of one-way ANOVA was used to investigate changes in sediment characteristics before (initial samples at 0 passes) versus after (final samples at 75 passes) vehicle traffic application.

ANOVA was also used to investigate the effect of repeated vehicle passes on sediment compaction. A series of three (i.e. separately for each zone; high-, mid- and low-shore) one-way ANOVAs were used to test the effect of sampling location (a fixed factor with two levels; inside versus outside of the vehicle track) on sediment compaction (measured as penetration resistance), with the number of vehicle passes applied as a covariate. Repeated-measures ANOVA was not conducted on these data because there were fewer replicate transects (i.e. n = only 3-4 transects per zone; total n = 10 transects) than time-steps. A second series of three one-way ANOVAs were used to determine if there were any effects of repeated vehicle passes on sediment compaction (measured as penetration resistance) after 75 vehicle passes (i.e. on completion of experimental traffic application), again testing for differences between sampling locations.

Potential sediment displacement by vehicles on Silver Sands Beach was estimated by extrapolation based on observed displacement and average summertime vehicle passes in the high-shore zone only on Silver Sands beach (using average vehicle track data presented in Chapter 2). The same was not done for other sections of the beach because there was no measurable response of sediments there to vehicle traffic application.

3. Results

In total 109 individual microtopography transects were completed over 10 vehicle transects. Of these, three vehicle transects each were conducted in the high- and mid-shore zone, and four in the low-shore. All transects included 75 vehicle passes, except the third high-shore transect, for which only 50 passes were possible because the area became impassable by the experimental vehicle due to the soft, churned sand. Overall, the high-shore was the only zone to respond to vehicle passes with measurable net displacement (Figure 4.2).

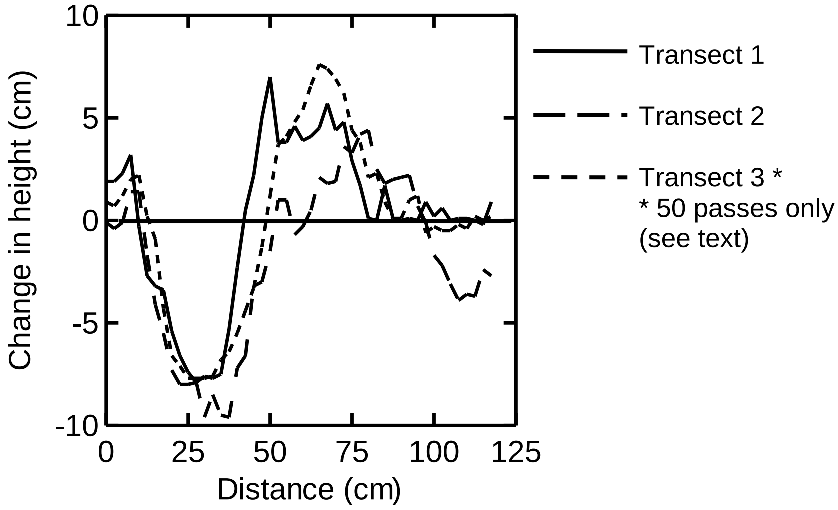
Overall, mean MGS and sorting values were slightly larger in the high-shore (i.e. coarser and less-well sorted sands) relative to the mid- and low-shore zones before experimental traffic application (Kruskal-Wallis test for differences among zones: MGS $H_{2d.f.} = 7.318$; $p = 0.026$; Sorting $H_{2d.f.} = 5.705$; $p = 0.057$; Figure 4.3). There was no apparent change in sorting, MGS or bulk density after vehicle traffic application (i.e. large and overlapping error bars in Figure 4.3; also non-significant when tested by ANOVA). Sediment moisture content increased from high- to low-shore ($H_{2d.f.} = 6.709$; $p = 0.035$) and did not respond to vehicle traffic application (Figure 4.3; non-significant when tested by ANOVA). Beach slope increased from the low- to the high-shore (Figure 4.3).

Sediment compaction

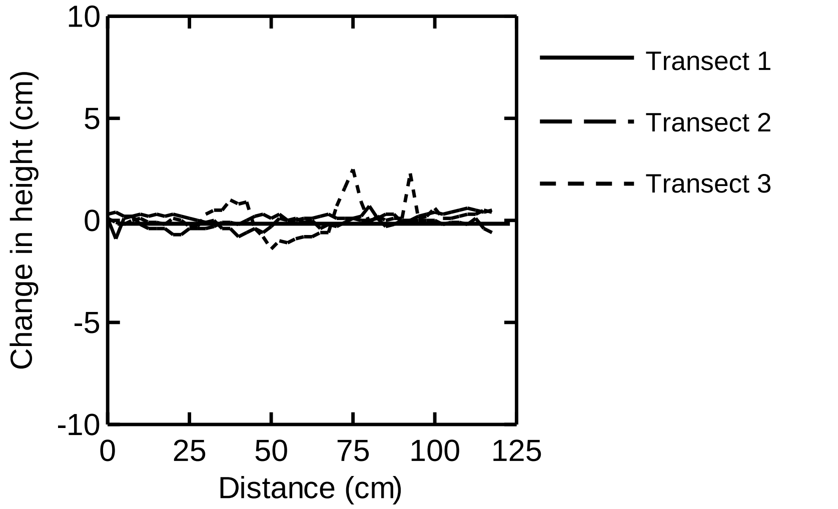
Penetration resistance (PR) was successfully measured on all three high- and mid-shore transects, and three of the low-shore transects (transects 1, 3 & 4). PR could not be measured on low-shore transect 2 because of the presence of too many cobbles in the sediment, preventing the instrument from being able to get a reading. Low-shore sediments were significantly firmer (as measured by penetration resistance) than mid- or high-shore sediments prior to vehicle traffic application (5.1±0.09 $kg.cm^{-2}$ versus 4.3±0.14 & 4.1±0.22 $kg.cm^{-2}$, respectively; $F_{2,42d.f.} = 12.817$; $p = 0.000$). PR tended to increase inside the vehicle track relative to the adjacent sediments in the high-shore, but was reduced inside versus outside the vehicle track for both the mid- and low-shore zones (Figure 4.4). In the high-shore zone, PR showed an initial decrease (i.e. softening of surface sediments) inside the vehicle track for the first 5 passes then an increase to

Figure 4.2: Change in topography (height) for each transect after 75 vehicle passes. The solid black horizontal line at 0cm height change indicates the original state of the beach, so negative values below are sediment ‘loss’ (i.e. via displacement &/or increased compaction), positive values above are ‘gains’ (i.e. via displacement-induced influx &/or decreased compaction).

a) High-shore



b) Mid-shore



c) Low-shore

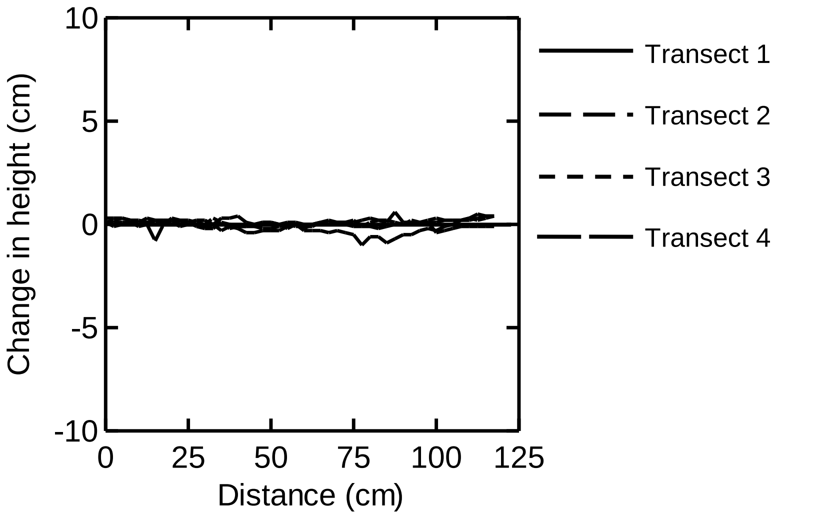


Figure 4.3: Initial (unfilled bars) and final (solid fill bars) mean values (±SE) for sediment characteristics, specifically a) mean grain size (MGS); b) sorting; c) percent moisture content; d) bulk density; and e) mean slope (slope values were constant for each transect, thus no 'initial' or 'final' slope value) for displacement transects conducted in each zone (high-shore *n* = 3; mid-shore *n* = 3; low-shore *n* = 4).

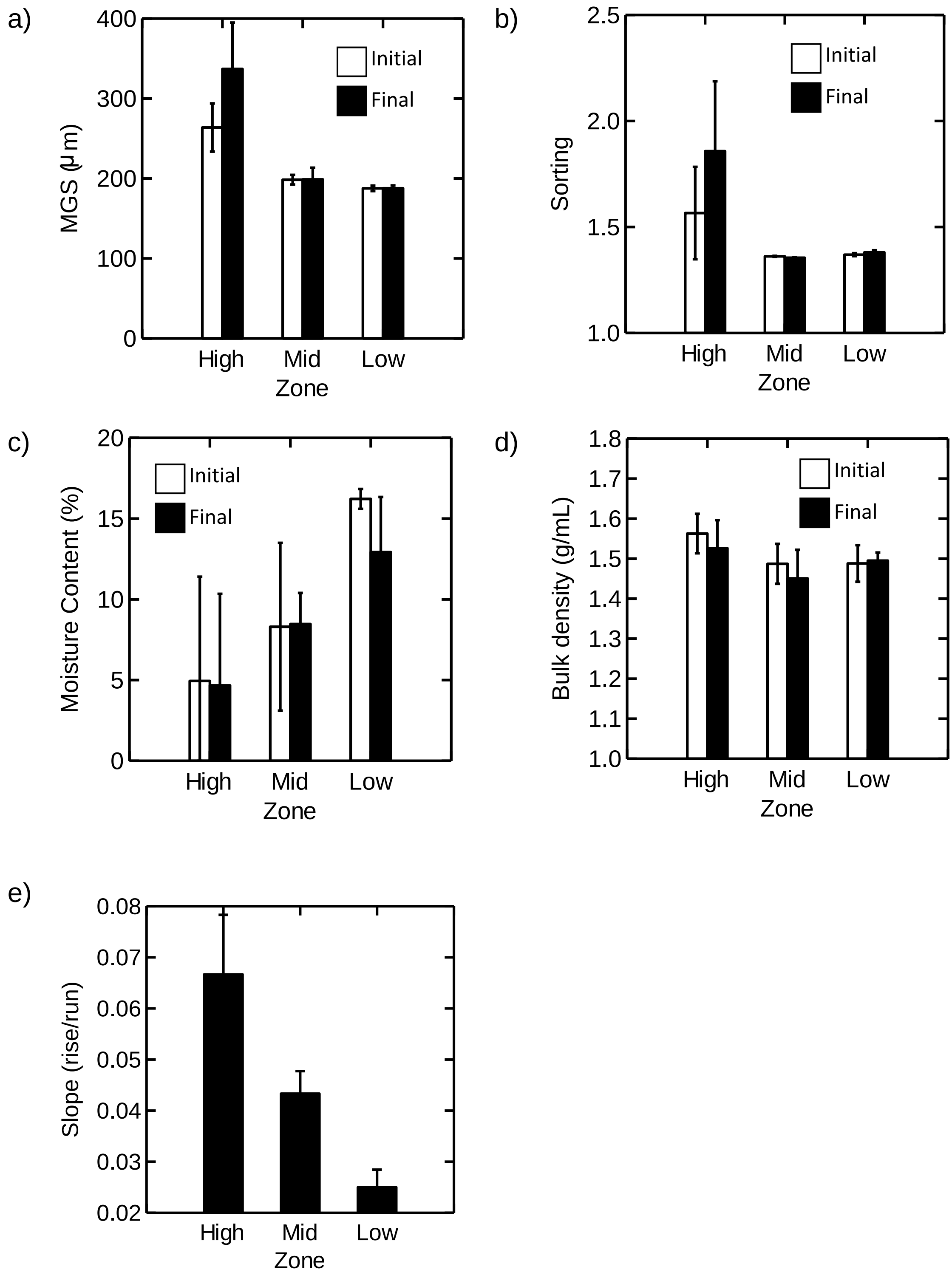
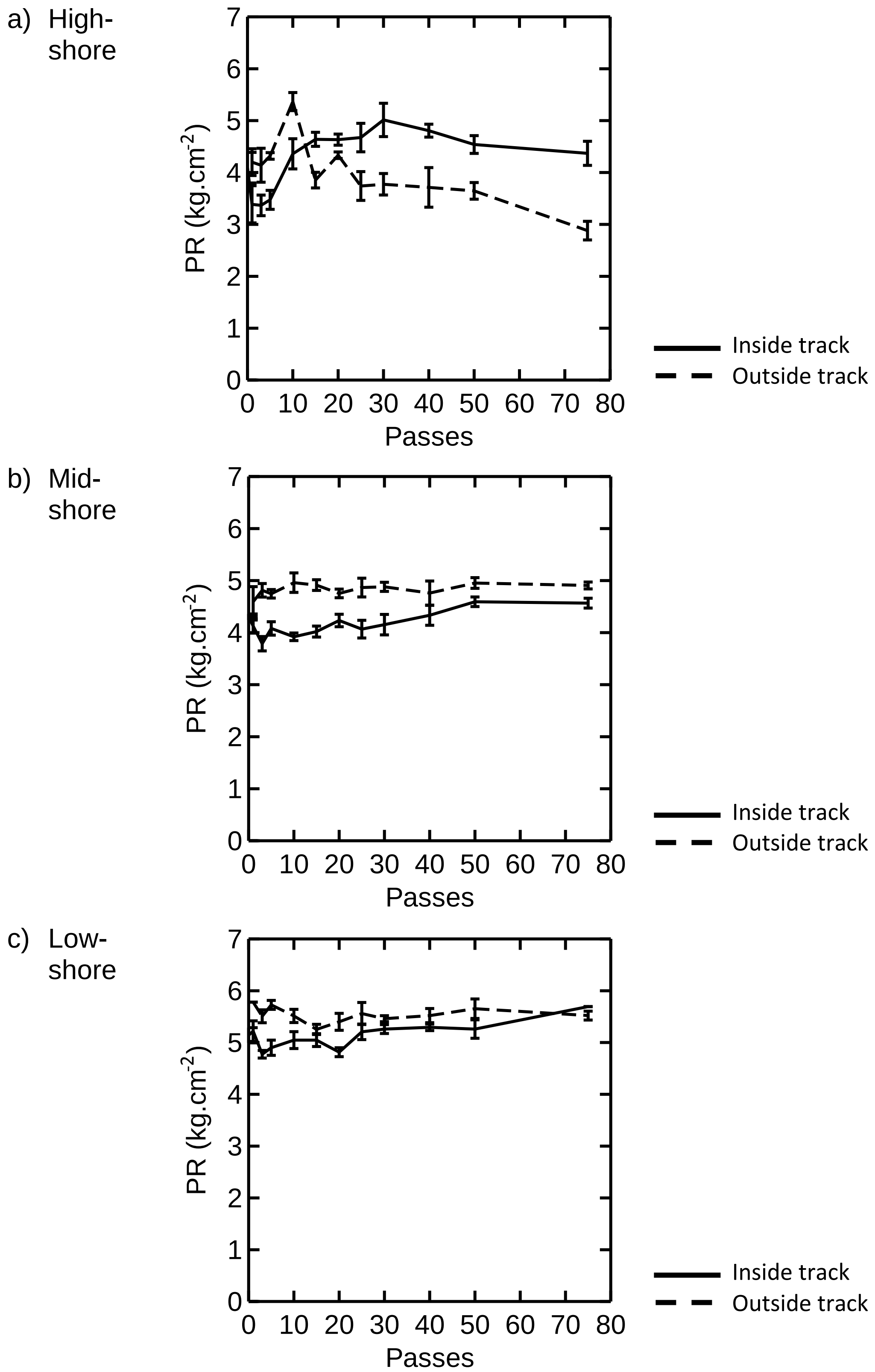


Figure 4.4: Patterns of penetration resistance (PR in kg/cm^2; separately for each zone) measured inside (solid line) and outside (dashed line) the vehicle track across 75 vehicle passes through the high-shore zone. Error bars indicate ±SE.



pre-traffic levels after 10 passes (Figure 4.4a). PR showed a similar but less pronounced trend for initial softening inside the track followed by surface strength increases to pre-traffic levels in both the mid- and low-shore zones (Figure 4.4b,c).

For all zones, there was a significant difference in penetration resistance (PR) measured inside and outside of the vehicle track (Table 4.1a). PR was greater inside the track relative to outside in the high-shore only; in contrast, mid- and low-shore sands showed decreased PR inside the vehicle track (Figure 4.5; Table 4.1b). At the completion of experimental traffic application, penetration resistance showed no significant differences inside versus outside of the track for any of the three zones (Figure 4.5; Table 4.1c).

Sediment disruption & displacement

Sediment displacement and disruption recorded wide ranges of values across the 10 transects, with no sediment disturbance measureable for any mid- or low-shore transect, resulting in minimal values for most variables of $0 cm^2$ (Table 4.2). Rut and mound sizes, areas and displacement measures (i.e. net down-slope displacement (Net DS) and net disruption) could only be calculated for the high-shore zone, because this zone was the only one to respond measurably to vehicle traffic (Figure 4.2). Net down-slope displacement increased steadily over the first 30 vehicle passes then plateaued at approximately $100 cm^2$ of sediment displaced (Figure 4.6a). Similar asymptotic trends were observed for track width, up- and down-slope mound heights and areas (not shown). The depth and area of the rut showed a steady increase (i.e. increasingly deeper rut with greater area; also not shown). Net disruption showed a trend for an initial but mild decrease (i.e. ‘negative’ disruption) between 0 and 5 vehicle passes, followed by a steady increase with increased passes to a final level of approximately $+50 cm^2$ disturbed (Figure 4.6b). The error associated with net disruption measurements also tended to increase with number of passes (Figure 4.6b). The area of the rut and the combined area of the up- and down-slope mounds was approximately equal (i.e. points lay on or close to the 1:1 line; Figure 4.7), with perhaps slightly smaller area in the mounds than the rut (i.e. a number of values below the 1:1 line; Figure 4.7a). Some values plotted well above the 1:1 line, these corresponded only to values from high-shore

Table 4.1: ANOVA table testing for differences in sediment compaction (measured as penetration resistance (PR in kg.cm^{-2}) at the completion of experimental traffic application; data 4th-root transformed to meet the assumption of normality) a) inside versus outside the vehicle track (Location factor; total *n* = 330 for mid- and low-shore; high-shore *n* = 216; some cases deleted due to missing data because PR instrument could not get a reading due to cobble stones; vehicle passes as a covariate); b) table of mean values for PR inside and outside the track for each zone (untransformed data); and c) ANOVA results comparing PR inside versus outside the vehicle track after completion of vehicle passes (total passes = 75; except one high-shore transect with 50 passes). Bold probabilities are significant.

a)

Zone	**Source**	**d.f.**	**MS**	***F*-ratio**	***p***
High-shore	Location	1	0.511	59.149	**0.000**
	Passes	1	0.017	2.013	0.157
	error	213	0.009		
Mid-shore	Location	1	0.239	90.897	**0.000**
	Passes	1	0.033	12.359	**0.001**
	error	327	0.003		
Low-shore	Location	1	0.100	18.402	**0.000**
	Passes	1	0.006	1.117	0.291
	error	303	0.005		

b)

Zone	**Location**	**Mean (PR)**	**SE**
High-shore	Inside track	4.005	0.097
	Outside track	3.027	0.085
Mid-shore	Inside track	4.171	0.049
	Outside track	4.832	0.051
Low-shore	Inside track	5.123	0.054
	Outside track	5.780	0.269

c)

Zone	**Source**	**d.f.**	**MS**	***F*-ratio**	***p***
High-shore	Location	1	0.027	2.138	0.155
	error	28	0.013		
Mid-shore	Location	1	0.008	1.869	0.182
	error	28	0.004		
Low-shore	Location	1	0.001	0.918	0.346
	error	28	0.001		

Figure 4.5: Bar graph showing penetration resistance (mean kg/cm^2 ±SE) inside (unfilled bars) and outside (solid fill bars) of the vehicle track on completion of experimental vehicle passes (*n* = 75 passes for all but one high-shore transect, *n* = 50; see text for explanation), separately for each zone (high-, mid- and low-shore).

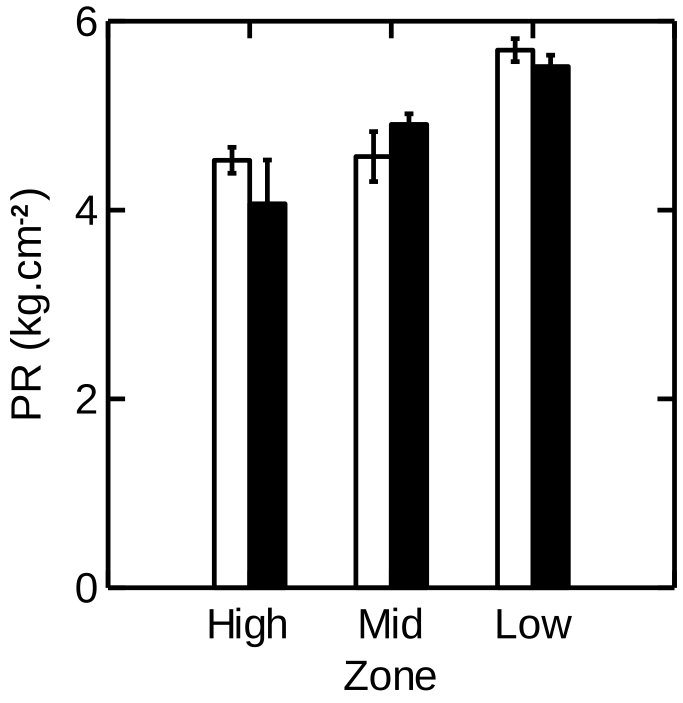
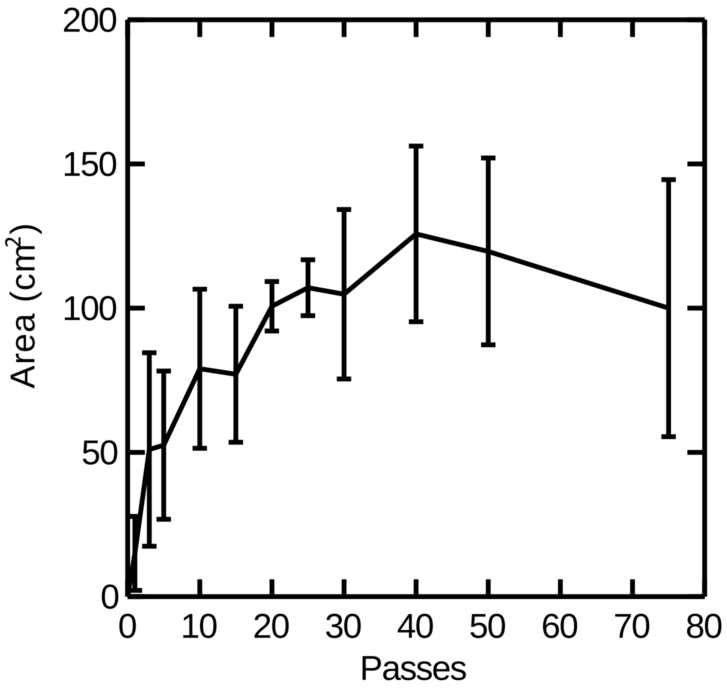


Table 4.2: Mean values and ranges of values for measured sediment disturbance variables across all zones after 75 vehicle passes.

Variable	Mean	Minimum	Maximum
Down-slope mound area (cm^2)	25.58	0.00	147.50
Up-slope mound area (cm^2)	3.36	0.00	23.25
Track area (cm^2)	46.53	0.00	250.50
Net down-slope displacement (cm^2)	22.22	0.00	124.25
Net disruption (cm^2)	17.58	-2.50	160.75

Figure 4.6: Measured a) net down-slope displacement; and, b) net disruption across 75 vehicle passes through the high-shore zone. Error bars indicate ±SE.

a) Net displacement



b) Net disruption

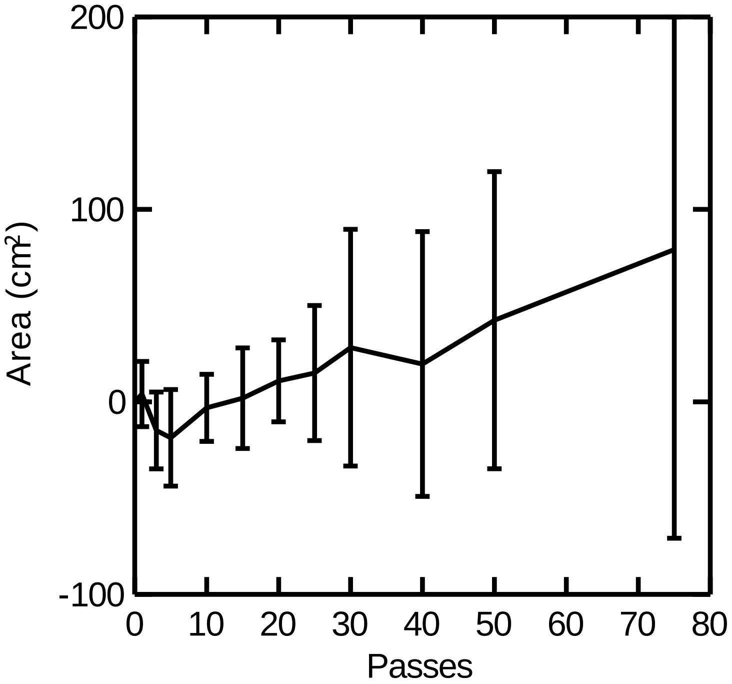
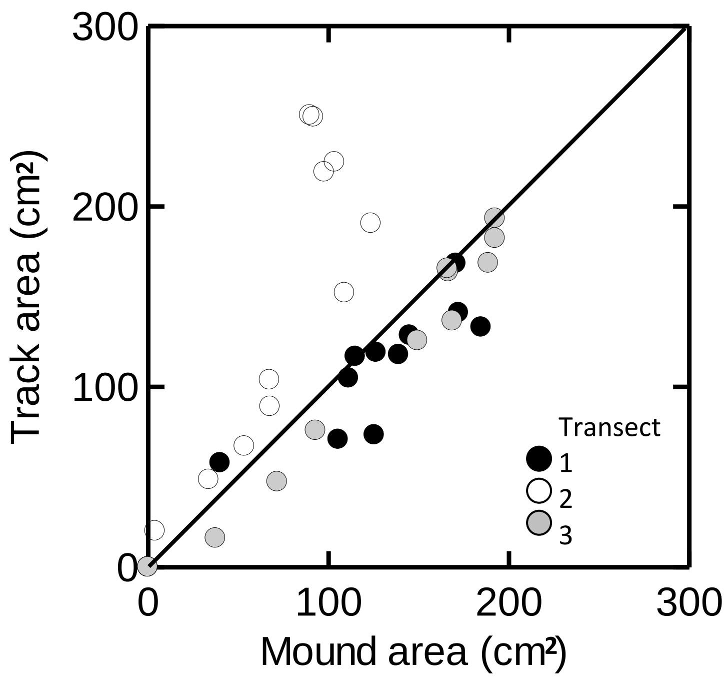
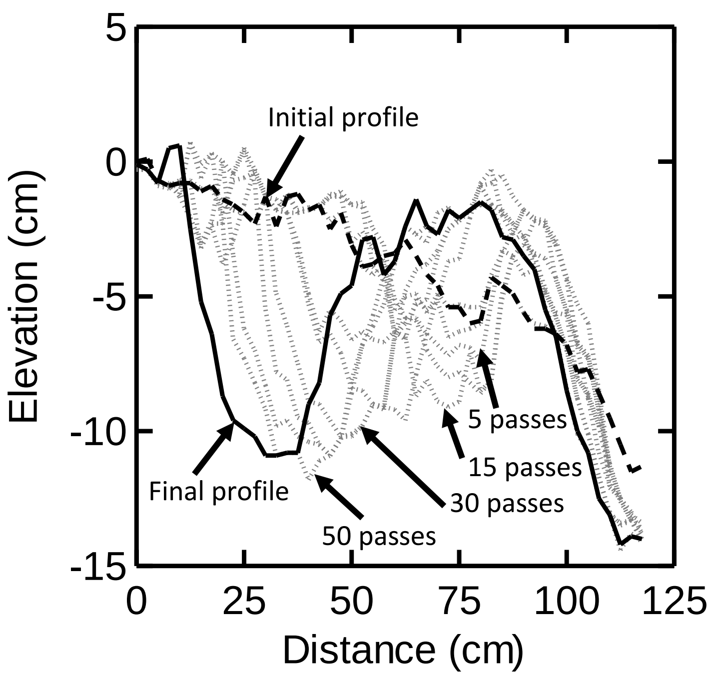


Figure 4.7: a) Scatterplot showing corresponding values for track (y-axis) and combined up- and down-slope mound (x-axis) areas for the three transects conducted in the high-shore zone (with 1:1 line included); and b) profile plots for each set of passes (initial = solid, dashed line; final = solid line; other sets greyed-out) for high-shore transect 2 showing how the track moved upslope across subsequent sets of passes.

a)



b)



transect 2, for which the vehicle track was not directly overlaid by each subsequent set of vehicle passes, resulting in the track moving towards the top of the transect (Figure 4.7b) and an accumulation of displaced sediment in the down-slope mound.

Factors important for sediment displacement & disturbance on Silver Sands

For all beach zones, both Net DSM displacement and Net disruption, initial sediment characteristics (MGS, sorting and % of sediments > 1mm) best explained observed patterns of sediment movements in all three beach zones, high-, mid- and low-shore (Table 4.3a). For the high-shore alone, Rho (ρ) was maximised at 0.582 for a combination of three variables (# passes, initial PR and track width) for Net DS displacement but only 0.186 for a single variable (# passes) for Net disruption (Table 4.3b). With the exception of Net disruption for the high-shore zone, for which there was only a poor correlation between sediment movements and sediment characteristics (i.e. $p > 0.05$), all other BIOENV tests were significant at $p<0.01$ when tested by the global BEST match permutation test (999 permutations).

Estimated sediment displacement by passes/over time

The potential for sediment down-slope displacement and disruption was also assessed for the high-shore zone only. Vehicle effects in the mid- and low-shore zones are expected to be minimal, due to the lack of response to experimental vehicle passes observed in these two zones (Figure 4.2).

To determine the potential for sediment disruption and displacement on Silver Sands Beach, two factors were considered important; firstly, the traffic volume experienced on Silver Sands Beach (i.e. the number of potential vehicle passes) and secondly, how many tracks are left by these vehicles. Vehicles driving on the beach can either create a new track on the sand or can choose to partially or totally overlap (i.e. follow) a track left by a previous driver. The latter is common on soft sands where conditions can be unpredictable. Because there is a plateau effect of repeated vehicle passes on sediment disruption and displacement, rather than a continuously cumulative one, the potential sediment displacement and disruption on this beach will be a range of values, rather than a straight-forward estimate.

Table 4.3: BIOENV analysis results showing sediment variables (MGS: mean grain size; degree of sorting and >1mm: the percent of the sample that had grain size greater than 1mm) selected in the top 3 ranking combinations (ρ rho values) to best explain observed patterns in Net DS displacement and Net disruption for a) all three beach zones combined; and b) high-shore zone only. The selection of variables in high-ranking combinations is indicated by ✓ (variable included) or ✗ (variable not included)

a) All zones

Net DS displacement (sample statistic ρ = 0.676; ***p* = 0.01**)

Rho (ρ)	Variables	MGS	Sorting	>1mm
0.676	3	✓	✓	✓
0.672	2	✓	✗	✓
0.670	2	✓	✓	✗

Net disruption (sample statistic ρ = 0.626; ***p* = 0.01**)

Rho (ρ)	Variables	MGS	Sorting	>1mm
0.626	3	✓	✓	✓
0.613	2	✓	✗	✓
0.608	1	✗	✗	✓

b) High-shore only

Net DS displacement (sample statistic ρ = 0.582; ***p* = 0.01**)

Rho (ρ)	Variables	# passes	$PR_{initial}$	$Width_{track}$	Slope
0.582	3	✓	✓	✓	✗
0.573	4	✓	✓	✓	✓
0.565	2	✗	✓	✓	✗

Net disruption (sample statistic ρ = 0.186; *p* = 0.17 NS)

Rho (ρ)	Variables	# passes	$PR_{initial}$	$Width_{track}$
0.186	1	✓	✗	✗
0.182	2	✓	✓	✗
0.166	3	✓	✓	✓

Table 4.4 shows theoretical net DS displacement predictions based on observed results for four (of the many hundred possible) hypothetical scenarios of Silver Sands Beach receiving 75 vehicle passes through the high-shore. It shows that fewer passes through an increased number of tracks results in increased net DS displacement (Table 4.4). Minimum (1.00 ±0.243 m^2) versus maximum (11.25 ±7.28m^2) theoretical DS displacement for this traffic volume (75 passes in total) are observed in the case of all drivers following the same track versus all drivers creating a new track, respectively (Table 4.4), with the latter being a 10-fold increase in DS displacement on the former.

Traffic volumes on this section of Aldinga Bay Beach vary throughout the year (see Chapter 2). Most drivers use the firmer sands of the mid- and low-shore zones when traversing the beach (pers. obs.), with only an occasional driver using the soft, dry sands of the high-shore. Still, this zone recorded some usage in both the open and closed seasons (Chapter 2). On average (over 34 transects conducted between April 2006 & May 2008) for Silver Sands Beach, 22.6% of all tracks on the beach-face were observed in the high-shore, with slightly more (23.4% of all tracks) in the summertime, when vehicles are legally permitted on the beach. Silver Sands Beach is accessed by one ramp for which daily ramp usage was recorded across four separate weeks in 2007/08 (see Chapter 2). Over these four weeks, this ramp received an average of 624.9 ±117.5 passes per day, approximating 312 vehicles (in theory, each vehicle entered and left the beach by this ramp). If 22.6% of these vehicles do traverse the high-shore, then this equates to approximately 70 vehicle passes through this zone, and potentially between approximately 1m^2 (all through one track) to 10.5m^2 (all through individual tracks) of sediment displaced down-slope (i.e. net DS displacement) per day, which equates to between 657,000 and 6,898,500 m^3 per year along a 1.8km long section of beach, not accounting for seasonality. This DS displacement could be all but eliminated by restricting drivers onto the mid- and low-shore zones.

Cobble bed displacement and disruption

Due to hazardous conditions it was decided not to undertake experimental trials in the high-shore cobble bed; however, some existing

Table 4.4: Potential down-slope displacement of sediment from the high-shore zone of Silver Sands for a total of 75 vehicle passes, but with four possible combinations of number of tracks (i.e. 75 vehicle passes through 1, 9, 11 or 75 tracks), representing a range of potential down-slope displacement estimates. In each case there are 75 passes of a vehicle but through different numbers of tracks (i.e. case 1 = all vehicle passes through one track; case 4 = all 75 vehicle passes through single (i.e. 75 separate) tracks). Calculations have been made based on measured displacement for a given numbers of passes (i.e. measured displacement for 1 pass = 0.150 ±0.097; 5 passes = 0.525 ±0.194; 10 passes = 0.790 ±0.209; 20 passes = 1.007 ±0.065; 25 passes= 1.071 ±0.073; and 75 passes = 1.000 ±0.243 m^2 of sediment). Because each four-wheel vehicle actually makes two tracks when it drives through sand, volumes estimated here can be doubled.

Case	Passes	Tracks	Potential Displacement (m^2) mean ±SE
1.	**75**	**1**	**1.000 ±0.243**
2.	20	1	1.007 ±0.065
	10	3	2.370 ±0.627
	5	5	2.625 ±0.970
	75	**9**	**6.0**
3.	25	1	1.071 ±0.073
	5	10	5.250 ±1.940
	75	**11**	**6.3**
4.	**75**	**75**	**11.250 ±7.275**

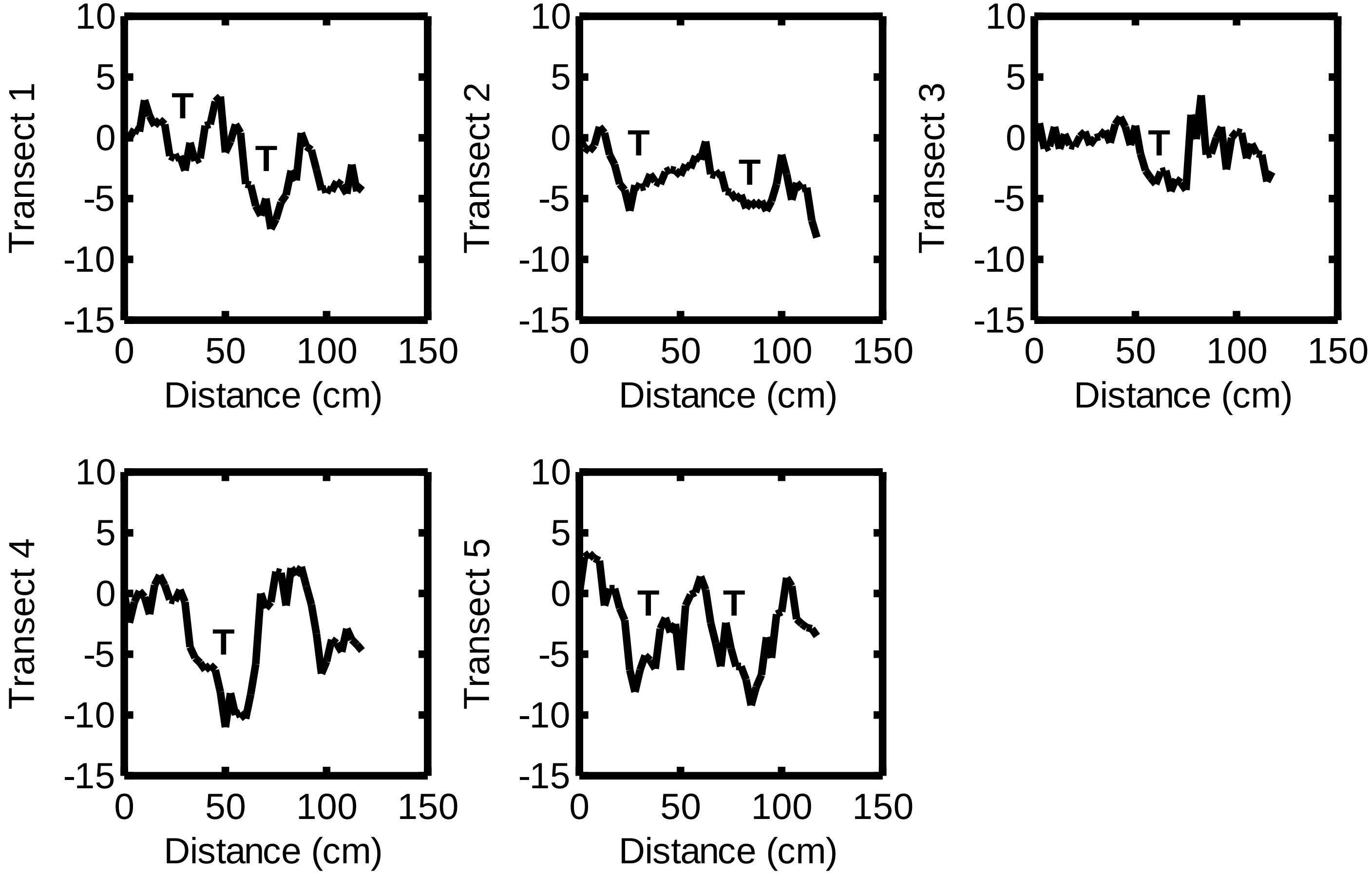
tracks through the bed were opportunistically measured in October 2008. Because the sampling was opportunistic in nature it is unknown how many times a vehicle had passed through each rut. In total, 8 tracks were measured across 5 separate cobble bed microtopography transects. Rut and mound sizes were similar in scale to those for high-shore experimental trials (Figure 4.8); however, estimation of displacement areas is not possible for these transects because baseline data are not available.

4. Discussion

As tyres pass over sandy sediments they exert forces and shear stresses on the substrate, resulting in compaction directly beneath the tyre and loosening of sand from around the zone of compaction (Webb 1983). For Silver Sands Beach, increased sediment compaction inside the vehicle track is suggested by a discrepancy in the rut and mound areas for the high-shore zone (i.e. see Figure 4.7a). Most points in this plot lie either on or below the one-to-one ratio line, indicating that there was more sediment missing from the track than was accumulated in the mounds. The same result was found by Anders and Leatherman (1987), which they attributed to increased sediment compaction at depth. Likewise, increased compaction at depth was observed in a dune system exposed to vehicle traffic relative to a dune system without traffic in North Carolina (Hosier & Eaton 1980). Compaction at depth was not investigated for Silver Sands Beach.

Experimental tests investigating different intensities of vehicular traffic upon sandy substrates have found significant positive log-linear relationships between the number of vehicle passes and compaction measures of the soil (Liddle & Greig-Smith 1975; Webb 1982). Liddle and Greig-Smith (1975) made repeated measurements of soil penetrability and bulk density after an increasing number of passes (0, 3, 4, 8, 16, 32, 64, 128, 192, 256 passes) in a track created in a sandy but vegetated dune environment. Similarly, for a sandy-loam/loamy-sand California desert soil, five independent treatment plots exposed to different levels of vehicle passes (0, 1, 10, 100 & 200 passes) were used to demonstrate increases in surface bulk density (down to 6cm; Webb 1982). A total of 256 vehicle passes down the dune track resulted in a 60% increase in soil strength and 16.7% increase in bulk density (Liddle & Greig-Smith 1975), and 200 passes through the desert sand

Figure 4.8: Cobble bed transects showing the pre-existing tracks measured (marked as ‘T’).



resulted in a similar increase in bulk density of 14.3% (Webb 1982). A similar increase in surface strength of 55% was shown on a track created in vegetated dune sands by 200 passes of a motorcycle, relative to a non-impacted control plot (Kutiel *et al.* 2000). However, for transects conducted on Silver Sands Beach, there was no significant relationship between sediment surface strength and the number of passes. Sediment surface strength (i.e. penetration resistance) in the high-shore zone showed no overall change from initial levels after applying 75 vehicle passes to an area. Instead there was a change in the degree of sediment compaction during the course of the experiment, which is highlighted by comparison to the results for surface strength changes in the sediments adjacent to the vehicle track, which showed decreased surface strength at the end of the trial. The area adjacent to the track became trampled unintentionally in the process of collection of samples and measurements during the experiment, an action that also resulted in the destruction of surface crusts. However, unlike within the track, there was no subsequent increase in surface strength adjacent to the track, and thus this increase in surface strength, and thus also sediment compaction, can be attributed to vehicle actions. Changes in sediment compaction in the mounds generated by sediment displacement were not measured in this study, but it is likely that sediments in the mound were less compacted than unaffected (i.e. 'outside' track) sediments and sediments within (i.e. 'inside') the track itself. Measuring penetration resistance across the entire displacement profile, rather than only the track and area around the track, in future studies would allow for investigation of sediment compaction changes in mounds adjacent to tracks.

The mid- and low-shore zones both showed either a slight reduction in sediment surface strength (mid-shore) or no response (low-shore) to vehicle traffic application (see Figure 4.4). Moisture content of the sediment can be a factor in compaction of sandy sediments. Theoretically, moist, non-cohesive (i.e. low clay content) sediments, such as beach sand, are able to resist compaction via the entrapment of air by water films in the interstitial spaces, thus dry sands are more susceptible to compaction than moist ones (Webb 1982). Very moist non-cohesive sediments are also susceptible to compaction (Webb 1982), as the sediment matrix becomes waterlogged.

Thus, both very dry (i.e. high-shore) and waterlogged (i.e. low-shore) sands should be more susceptible to compaction than moist sands (i.e. mid-shore). After the application of 75 vehicle passes on a North Stradbroke Island beach in Queensland, Australia, Schlacher *et al.* (2008b) instead found a reduction, rather than an increase, in compaction of dry, high-shore sands (water content <18%) and increased compaction of moist, low-shore sands (water content >18%). Results for Silver Sands Beach suggest that, for these dry, high-shore sands (water content ~5%), there is an initial reduction in compaction (as surficial crusts are destroyed) followed by increased compaction, a reduction in compaction for damp, mid-shore sands (water content ~7%) and resistance to compaction of moist, low-shore sands (water content ~15%). The results of these two studies combined fit the theory described by Webb (1983); after the initial destruction of surficial salt crusts, there is increased compaction of dry sands, resistance to compaction of damp sands and increased compaction of wet sands.

Experimental conditions held constant my study were broadly similar to those of Anders & Leatherman (1987), except that vehicle weight was slightly greater for the Rav4 vehicle I used (i.e. GVM for the Rav4 was 2100kg as opposed to 1600kg for the vehicle used by Anders & Leatherman 1987). Both mean values and value ranges for sediment displacement values (i.e. mound and track areas, net displacement and disturbance) measured in this study were all much smaller than values obtained using the same methods by Anders and Leatherman (1987) for a beach on Fire Island, New York, US. Only approximately half as much sediment was displaced downslope by vehicle tyres in my study (mean net DS displacement = 22.22cm^2) as was recorded by Anders and Leatherman (1987); mean net DS displacement = 49.40cm^2 per cm, and there was only a fraction of the net disruption observed (mean = 17.58cm^2 in this study versus 91.94cm^2 per cm; Anders & Leatherman 1987). Both net down-slope displacement and disruption areas measured by Anders and Leatherman (1987) were converted into volume estimates of 'cm^2 per cm' by assuming that measurements were representative of conditions along 1cm of beach (F. Anders, pers. com.), and so estimates for the areas obtained from my study (this thesis) can be directly compared to those published by Anders and Leatherman (1987).

Estimated annual volumes of net seaward movement of sand and potential erosion were much greater for Silver Sands (between 657,000-6,898,500m^3 per year) than the Fire Island beach (119,300m^3 per year; Anders & Leatherman 1987), owing to higher traffic volumes at Silver Sands (approximately 113,880 per year for Silver Sands as opposed to 45-65,000 at the time of sampling on Fire Island; Anders & Leatherman 1987). Likewise, sediment disruption was estimated at 12,573 – 38, 018m^3 per day based on measured rut dimensions for two North Stradbroke Island beaches (Schlacher & Thompson 2008). The traffic volumes for these beaches (range 2.69 – 6.35 & 2.38 – 8.06 tracks.m^{-1}; Schlacher & Thompson 2008) is greater than that of Silver Sands (track density (n = 32 transects) range = 0.00 – 1.39 tracks.m^{-1}), as were measured rut depths (max = 9.6cm for Silver Sands versus 28cm for Queensland beach; Schlacher & Thompson 2008). Estimates for disruption obtained in my study and those of Schlacher and Thompson (2008) cannot be directly compared owing to the use of vastly different methods for quantifying sediment mobilisation by vehicle tyres. However, there may be a trend among these three studies for increasing mobilisation of sand with increased vehicle traffic on beaches. This trend could be investigated further using a series of studies utilising the same methodologies across a number of beaches subjected to a range of vehicle usage intensities. Such ranges in vehicle usage intensity exist along the South Australian coastline (i.e. see Chapter 2).

How much of this displaced sand is actually eroded will depend on hydraulic and aeolian processes (Anders & Leatherman 1987) but, unlike the Fire Island beach, there is rarely a berm feature present on Silver Sands Beach, and so at least part of the high-shore is frequently wetted by spring high-tides (approx. twice per month). Thus the area of greatest sediment disturbance is subject to frequent wetting by the tide and there is the potential for sediment erosion. Unfortunately, traffic volume data obtained from ramp counts is biased towards summer months (3 weeks of sampling effort in summer versus 1 week in winter), and so potential annual sediment volume losses stated here for Silver Sands Beach are likely overestimates.

Anders and Leatherman (1987) observed that net seaward movement of sand could have been minimised on the Fire Island beach by restricting driving to two tracks on the foreshore in winter and to two tracks in the back-berm area in summer. In the case of Silver Sands Beach, which rarely forms a summer berm, net seaward movement of sand can be all but eliminated by restricting driving to the mid- and low-shore area because these zones exhibited no measureable response in sediment movements after 75 vehicle passes.

Sediment characteristics, specifically MGS, sorting and the fraction of the sediment that was coarse (>1mm) were important factors in determining sediment displacement and disruption across all three zones on Silver Sands Beach. These were all factors that distinguished the high-shore from the other zones on Silver Sands Beach (e.g. see Figure 4.3), and given that the high-shore was the only zone to show any measurable response to sediment displacement, the selection of these variables makes sense. In the high-shore alone, the number of passes, the initial surface strength of sediments and width of the vehicle track were important factors in determining the displacement and disruption of high-shore sediments. Beach slope, number of passes and the degree of vertical compaction were selected as variables important in determining net down-slope displacement in Anders and Leatherman's (1987) study on the Fire Island beach. Beach slope measured on transects in the high-shore zone of Silver Sands Beach had a narrow range (slope (rise/run) = 0.05-0.08), and so was less likely to be selected in the BEST (BIO-ENV) analysis than other variables with wider ranges of values. Net down-slope displacement showed a positive relationship with number of passes, steadily increasing before plateauing after approximately 40 passes (see Figure 4.6), thus, to a point, sediment displacement increases with increasing vehicle passes but then stabilises. A positive relationship between net downslope displacement and number of passes was also observed in Anders and Leatherman's (1987) study.

For Silver Sands Beach, penetration resistance (also a measure of vertical compaction) inside the vehicle track in the high-shore zone showed an initial decrease, as the surficial salt-crust was broken by the actions of the tyres, followed by a gradual increase in surface strength, owing to compaction of the sediments. The width of the vehicle track was a variable not included in the analysis by Anders and Leatherman (1987). The vehicle track for one of the high-shore transects was not directly overlain after each set of vehicle passes, and there was a migration of the track from the centre of the profile towards the top (see Figure 4.7b). Subsequently, the track width increased with each set of passes and there was an increase in the amount of sediment displaced down-slope for this transect relative to the remaining transects where the track was more accurately overlain after each set of passes. This result, obtained inadvertently, indicates that driver precision (i.e. the ability to drive exactly within a track left by a previous driver) may be a factor in the realised sediment displacement.

Interestingly, sediments of both the high- and mid-shore zones had the same initial surface strength (i.e. no difference in penetration resistance) but, unlike the high shore, the mid-shore zone showed no measurable sediment displacement or disturbance response, even though initial penetration resistance was selected by BEST(BIO-ENV) as an important factor in determining sediment displacement. The main physical differences between these two zones were that the high shore had drier, coarser sediments and a steeper profile than did the mid shore. The presence of moisture in non-cohesive (i.e. low clay content) sediment bodies provides additional strength to the sediment matrix, because of the entrapment of air by water films in the interstitial spaces (Webb 1982). Also, beach slope has been shown to be a factor in sediment displacement, with increasing down-slope displacement with increased slope (Anders & Leatherman 1987). Thus, although these factors were not selected by the BEST(BIO-ENV) analysis as being important in determining sediment displacement and disruption, they may have contributed to differences in sediment movements observed among zones. In addition to these physical characteristics defining the high- and mid-shore zone, it was difficult to perfectly overlay the vehicle track in the mid-shore with subsequent sets of passes, because the track was difficult to observe the track from the drivers position. Subsequently, tracks through mid-shore transects often became much wider than the width of the tyre (and noticeably wider than tracks in the high-shore), thus spreading vehicle effects over a wider area. There was no significant difference in the width of the track among zones ($F_{2,113}$ = 0.989; p = 0.375), but there was a trend for tracks in the HS to be narrowest, then LS and MS widest. Thus, a combination of moister sands, flatter beach slope and wider spread impact may have combined to cause a lack of response of the mid-shore sediments to displacement and disruption by vehicles.

5. Conclusions

Although sediment down-slope displacement by vehicle tyres in individual tracks on Silver Sands Beach was lower than that previously observed by Anders and Leatherman (1987), annual net displacement was far greater. Thus the results from Silver Sands Beach show the effect of increased traffic volumes on sediment movements, with a six to 60 times increase in estimated annual net down-slope displacement with only an approximate doubling of vehicle traffic. These results also show the importance of testing impacts observed on other beaches under local conditions.

Expectations and predictions based on information from the scientific literature were supported for this chapter (see Chapter 1, Figure 1.5). Sediment displacement and disruption were far greater (indeed, were only recorded) in the high-shore zone, relative to the mid- or low-shore zones.

Reduced down-slope displacement was observed on Silver Sands Beach, a relatively flatter, featureless beach compared to the beach studies by Anders and Leatherman (1987), supporting the hypothesis of these authors that sediment displacement would be reduced on flatter beaches without a berm, although they were referring to winter profile beaches in their region (Anders & Leatherman 1987).

The results of this study on Silver Sands Beach are, however, severely limited by low levels of replication (i.e. only 3-4 transects conducted in each zone). Further transects at Silver Sands were not possible due to time and funding constraints. Initially, another study design was trialled to investigate sediment movements on sandy beaches on a broader scale, by tracking the movements of markers buried in the beach face over a period of several months (see Appendix 4.1). Unfortunately, this initial study design was unsuccessful, a result that is attributed to high natural levels of sediment movement and turnover that were not anticipated during the planning stages.

Measurement of the effects of vehicles on beach-face rutting, specifically displacement and disturbance of sediments, is essential for the management of beach driving and mitigation of any impacts on any beach. Although these results are quite limited they do clearly indicate that the down-slope displacement and potential erosion of large volumes of beach face sediments can be avoided with one simple management practice, that is, restriction of driving to the mid- or low-shore and recommend driving in only a single track in the high shore zone when necessary on beaches open to vehicles in southern metropolitan Adelaide, to minimise habitat disturbance. That this result was consistent between two studies, looking at different beaches in different decades with different levels of vehicle usage also indicates that this restriction might be good practice wherever vehicles are permitted to drive on the intertidal beach face.