CHAPTER 7: GENERAL DISCUSSION

Key findings

I have several main findings regarding the impacts vehicles on beaches. Firstly, vehicles appear to subtly degrade the physical environment of the beach rather than completely destroying it. The findings of Chapter 4, that vehicles were capable of mobilising large volumes of sediment, support previous studies identifying vehicles as a major contributor to physical sediment disruption and compaction (e.g. Anders & Leatherman 1987; Schlacher & Thompson 2008). Secondly, the findings of Chapter 5, that macrofaunal communities on beaches with vehicle access were depauperate in nature, support the body of literature suggesting that vehicles can have negative effects on macrofauna on sandy beaches. This thesis also offers some evidence that macrofaunal communities not directly affected by vehicles (i.e. via having no overlap of usage zones; *sensu* Schlacher & Thompson 2008) may still be negatively affected in an indirect way. To my knowledge, the effect of vehicles on ecosystem links (e.g. food chains) and wrack habitat quality or the spatial distribution of vehicle impacts on macrofauna has yet to be investigated. I view this process oriented work as the next step forward in quantifying vehicle impacts on the macrofaunal organisms of sandy beaches.

Finally, it is clear that the beaches studied in this thesis are subject to a high degree of natural variation. Much small-scale spatial and temporal variation was inherent in all aspects investigated or the beaches studied, and tended to override many possible differences among beaches based on vehicle access alone (see Chapters 3, 5-6). These beaches are all subtly different from each other and this is reflected in my results. This last finding highlights the importance of good study design when working in highly unpredictable and variable systems, including sandy beaches. Replication within the levels of a factor of interest is especially important to allow separation of any impacts of that factor from natural variation that may otherwise be mistaken for an effect.

In general, the work undertaken in each chapter of this thesis (discussed in section 4 of Chapters 2-6 and summarised in Table 7.1) supported expectations and predictions made from the literature in Chapter 1 (see

Table 7.1: Summary of findings versus expectations (see also Fig. 1.5) for each chapter, split where possible into within- and between-beaches comparisons. Some expectations relate only to hypotheses about closed sections on open beaches, and so between-beach comparisons were not applicable (denoted N/A).

Chapter	Expectation	Finding	Supported	
			Between beaches	**Within beaches**
2	Greater vehicle usage on open beaches relative to closed beaches or sections	Much higher usage of open beaches by vehicles than closed beaches/sections	Yes	Yes
	Some vehicle usage of closed beaches/sections	Some usage recorded on all closed beaches & sections surveyed Usage on seasonal closure at Silver Sands not reduced during closure period relative to open section on same beach, thus closure is ineffective	Yes	Yes, but Silver Sands closure not effective
3	Steeper high-shore due to sediment displacement on open beaches relative to closed beaches or sections	No difference between open & closed beaches Open sections steeper than closed sections on the same beach Open sections displayed greater slopes but this observation is complicated by the presence of the cobble bed, which is exposed at Sellicks & Moana, an effect that may be natural for these beach sections or may itself be a result of vehicles	No	Yes, but cobble beds on open sections complicate results
	Increased compaction of sediments on open beaches or sections relative to closed beaches or sections	Increased compaction of sediments observed on open beaches in mid-winter of most years, not otherwise. Possible compaction of sediments at depth (Anders & Leatherman 1987) that are exposed after erosion from winter storms Compaction similar among bay sections High susceptibility of sediments on study beaches, especially at Aldinga Bay, to compaction due to the presence of cobbles mixed with otherwise fine sands, & hence poorly-sorted sediments	Some support	No

Table 7.1: cont.

	Altered grain size on open beaches relative to closed beaches or sections	Trends for finer sediments on open beaches No difference between open & closed beaches or sections based on access, only spatial variation among beaches	Yes	No
4	Greatest sediment disruption & displacement in high-shore, with relatively low displacement for moister, flatter mid- & low-shore zones	High-shore was the only zone tested that respond with measurable sediment displacement even after 75 experimental vehicle passes	Yes (within- & between-beaches type comparisons not applicable for Chapter 4)	
	Increased sediment compaction in tracks	Compaction inside the track only observed in the high-shore zone Compaction in tyre tracks was seen to initially decrease in high-shore sands as surface crusts were destroyed, then increase with increased application of experimental vehicle passes Differences were observed among zones, most likely related to moisture content of the sediments	Mixed support Yes – but only in high shore No – for mid-shore – loosening of surface sediments observed instead No – for low-shore – no difference observed	
	High-shore most susceptible to increased compaction by vehicles due to dry sands	High-shore sediments displayed the most change in compaction with increasing number of vehicle passes, with an initial decrease in surface strength followed by an increase in sediment compaction	Yes	
5	Vehicle use of the beach will not alter the amount or composition of wrack deposited	Vehicle access was not a significant factor in determining the amount or composition of wrack on the study beaches Impacts of vehicles on quality of the wrack resources are unknown	Yes	Yes
	Seasonal shifts in amount of wrack deposited on beaches concurrent with natural seasonal variation in beach profiles	Both small-scale spatial & temporal variation in wrack cover & composition & beach profiles detected for within- & between-beaches comparisons	Yes	Yes
	Reduced abundance & diversity	Reduced macrofaunal occurrence & altered community structure on open beaches	Yes	No

Table 7.1: cont.

	of macrofauna & altered community structure on beaches with vehicles	relative to nearby closed beaches Depauperate macrofaunal communities across bays, regardless of vehicle restrictions or period of closure. No refuge or recovery for macrofaunal communities evident in recently closed sections, despite 3 and 15+ years of closure to date at Aldinga and Moana Bays respectively		
	Patterns in macrofaunal response to vehicles will mirror patterns in peaks of vehicle usage, with greatest impacts on macrofauna after peak vehicle usage period (i.e. post-summer)	Macrofauna increasingly absent from cores taken after peak period of vehicle usage (post-summer) on open beaches relative to nearby closed ones Depauperate communities across beaches with open sections throughout the year, some peaks in abundance at Sellicks for mid-winter & pre-summer sampling occasions	Yes	Mixed – no generally, but peaks in abundance in mid-winter at Sellicks
	Vehicle closure sections on open beaches will act as refugia for macrofauna, with increasing benefit observed with increasing time period of vehicle exclusion	Depauperate macrofaunal communities seen across beaches with open sections regardless of closure, no hard evidence for recovery post closure, even after 15+ years at Moana	N/A	No
6	Vehicle beaches will show increased sediment compaction, with reduced porosity & habitat quality, resulting in depauperate meiofaunal communities on beaches with vehicles	Small range in values for abiotic variables among beaches or beach sections No differences in meiofaunal abundance, species richness or community structure among beaches or beach sections based on vehicle access Some evidence to suggest increasing vehicle activity may cause deterioration of relationships between meiofaunal community structure & the measured environmental variables. The mechanisms of this still need to be explored.	Some support	Some support
	Vehicle closure sections on open beaches will act as refugia for meiofauna	No difference in the meiofaunal abundance or species richness between sections open versus those closed to vehicles but some differences in community structure are evident. Some evidence that relationships between meiofaunal community structure in closures & the measured environmental variables are stronger at Moana Bay where closures have been established for longer (and are more effective; Chapter 2) than those at Aldinga	N/A	Some support

Figure 1.5). There were, however, some exceptions. Predictions for increased beach slopes, altered grain size and increased sediment compaction on beaches with vehicles were only partially supported, with inconsistent results for within- and between-beaches comparisons (Chapters 3 & 6) or zones (Chapter 4). Likewise, there were no apparent differences in macrofaunal communities in the closed sections of open beaches, and no apparent recovery of these organisms in closures after vehicle exclusion, even though there was some support for closures being beneficial for the group of smaller organisms, the meiofauna.

Spatial scales of physical effects

The use of within- and between-beaches comparisons have been integral in this thesis and has highlighted that, although some impacts have been detected in comparisons between beaches with different vehicle access, these are not always apparent within sections of the same beach with different vehicle use, or *vice versa*. The former case suggests an impact of vehicles that may extend beyond the zone of direct influence (e.g. depauperate macrofaunal communities in vehicle closures on Bays also with open sections; Chapter 5) while the latter indicates vehicle impacts on a beach may be overridden (and hence obscured) by a high degree of variability among beaches (e.g. increased beach slopes only observed on open sections in within-beaches comparisons but not in comparisons between-beaches; Chapter 3).

Chapters 3 and 4 have highlighted the difference in response of the physical beach-face to vehicles when responses are measured at different spatial scales. There was a discrepancy between large volumes of sediment displacement by vehicles (i.e. measurements made on a small spatial scale – tracks; Chapter 4) and the lack of difference seen between beach profiles of open versus closed beaches (i.e. on a larger scale – beaches; Chapter 3). Across all nine beaches sampled in this study (see Figure 1.3), there were net gains in beach cross-sectional area of 17-68m^2 per year (Chapter 3) during the three years of sampling, with no notable differences between beaches that were open versus those closed to vehicles (open range 15-68m^2/y; closed range 1-65m^2/y). However, the net downslope displacement estimated for Silver Sands Beach, based on measured displacement

(Chapter 4) and vehicle usage data (Chapter 2) indicated a potential loss of between 365 and 3800m^2 of sediment per year, not accounting for seasonality. Comparison of these two results indicates that accretion of sediments on open beaches has the potential to be severely impeded by downslope displacement of high-shore sand by vehicle tyres (i.e. net accretion observed on open beaches is an order of magnitude lower than the estimated potential downslope displacement), even though differences in beach profiles observed in this study were highly variable and inconsistent through time and space (Chapter 3) and most likely related to geological and oceanographic processes rather than vehicle impacts.

Alternatively, the actions of vehicle tyres mobilising sediments in the high-shore near the dune toe may increase the rate of sediment transfer from the dune to the beach, by destabilisation and mobilisation of sediments in the upper high-shore and dune toe, resulting in an increase in beach-face area but loss of sediment from the dunes. Alternatively increased wind erosion of destabilised high-shore sediments may result in an increased transfer if sediment to the dunes. This study did not incorporate investigation of any potential negative effects of vehicles on the dune environment, because vehicles using these beaches do not drive in the dunes. However, it is possible that the actions of vehicles may disrupt sediment exchange between the beach and the dunes or near-shore marine habitat (i.e. attached bars). By rutting the sand and destroying surficial crusts, vehicles increase surface roughness and sediments are more susceptible to aeolian transport (Anders & Leatherman 1987). A third and more likely explanation, however, is that this contradiction between small-scale displacement and large-scale profile measurements indicates that the actions of vehicle tyres mobilising sediment may be highly localised and thus insignificant on a larger (i.e. whole beach) scale, in comparison to natural rates of sediment accretion and erosion on these beaches.

Potential effects on macrofauna from physical disturbances

In this thesis, a number of negative effects on the physical structure of the dry sands of the high-shore zone were observed (see Chapters 2-4). Further, a number of additional negative impacts are known from the literature. Specifically, vehicles have been shown to destroy the surficial salt crusts that form on high-shore sands, heavily rut the high-shore between the dunes and the drift line and cause significant mobilisation and disruption to surface sands in the high-shore (Anders & Leatherman 1987; Schlacher & Thompson 2008 also see Chapters 2 & 4, this thesis). Additionally, Schlacher *et al.* (2008c) noted a lack of insect species in the high-shore zone of vehicle-disturbed beaches. Likewise, this thesis has shown that the wrack-associated macrofaunal communities of beaches closed to vehicles are typified by a number of semi-terrestrial (i.e. the isopod *Actaecia pallida*) and terrestrial (i.e. *Cafius australis* & *Aphela phallenioides*) species that are generally absent from macrofaunal communities of open beaches (see Chapter 5). These results together suggest that these macrofauna that occur in the high-shore habitat are particularly vulnerable to vehicle effects.

Physical disturbances of beach sediments are great in the soft sands of the high-shore and back-beach zones are large, and these disturbances may contribute, at least in part, to observed decreases in beach macrofaunal abundance, species richness and altered community structure on vehicle-disturbed beaches. A number of macrofaunal species that utilise the intertidal beach-face are semi-terrestrial (e.g. some species of isopods and amphipods) or terrestrial (e.g. insects, spiders, birds) in origin, especially those that feed or shelter in wrack accumulations (Kirkman & Kendrick 1997; Colombini & Chelazzi 2003; Olabarria *et al.* 2006; Ince *et al.* 2007). Many of these species either reside in the dune habitat above the beach and move into the high-shore to access the intertidal zone or remain buried in the sand when not foraging or feeding (Hale 1927-29; Matthews & Queale 1997).

Severe rutting of the beach between the dunes and the drift-line may retard the movement of crawling macrofauna between the dune and intertidal beach habitat by trapping fauna and potentially exposing them to vehicle traffic when vulnerable on the sands surface when most macrofaunal organisms are most susceptible to crushing by vehicles (e.g. see Wolcott & Wolcott 1984; van der Merwe & van der Merwe 1991; Schlacher *et al.* 2007). Heavy rutting of the intertidal beach by vehicle tyres was found to retard the progress of loggerhead turtle (*Caretta caretta caretta*) hatchlings from their nests to the surf zone on beaches in North Carolina (Hosier *et al.* 1981). Fauna trapped or sheltering in ruts are also at risk of being crushed by drivers using the tracks left by a previous vehicle (a common practice when traversing the soft, high-shore sands; pers. obs.). For example, the chicks of birds nesting on the beach have been observed sheltering in vehicle ruts (Godfrey & Godfrey 1981). The increased metabolic cost of traversing the uneven rutted terrain may also negatively affect macrofauna.

Decreased stabilisation (i.e. loss of surficial salt crusts) and increased mobilisation (i.e. displacement and disruption from rutting) of high-shore sands may also affect macrofauna attempting to construct burrows in this habitat (Schlacher & Thompson 2008). It has been suggested that burrowing crabs may be negatively impacted by sediment instability following the destruction of surficial salt crusts (Schlacher & Thompson 2008). Increased metabolic costs from continuously reconstructing burrows and from tunnelling to the surface after being displaced with mobilised sediment is suggested by Schlacher and Thompson (2008) as an indirect mechanism for vehicle impact on these populations that requires further investigation. Semi-terrestrial burrowing crustaceans such as *Talorchestia quadrimana* and *Actaecia pallida* (Hale 1927-29) that occur on the beaches studied in this thesis may be similarly affected by destabilisation and mobilisation of surface sediments. Sediment instability may be a factor contributing to the reduced abundances of these species on beaches in my study region with vehicles, relative to nearby closed beaches.

Sizes of responding organisms versus spatial scales of impacts

There were vastly different responses of the two size-groups of beach fauna sampled in this study, the meiofauna (Chapter 6) and the macrofauna (Chapter 5), to vehicle closures on beaches compared with sections open to vehicles. Wrack-associated macrofaunal communities were depauperate on beaches open to vehicles relative to nearby closed beaches (despite the presence of wrack on both), and this effect appeared to extend to include the closure sections of beaches when compared with sections permitting vehicle access (Chapter 5). On the other hand, there were no apparent differences in the meiofaunal communities from beaches that were open versus those closed to vehicles but some indication that meiofaunal communities responded positively to vehicle closures on beaches compared with open sections (Chapter 6). Thus the spatial scale of vehicle impacts on the macrofauna alone seems to extend beyond the area of direct vehicle exposure and into closure sections on open beaches. The difference in response to vehicles of these two size-groups of beach fauna is most likely due to different spatial scales of beach utilisation.

Wrack-associated macrofauna most likely utilise a relatively large area of the beach although the actual mobility of many key species remains unknown (Schooler *et al.* 2009). The amount, composition or location of wrack deposits on intertidal beaches are highly unpredictable, and wrack can be considered an ephemeral resource on beaches (Colombini & Chelazzi 2003). There was a high degree of spatial and temporal variability detected in the composition and amount of wrack deposited on the study beaches (Chapter 5). Any animal reliant on an ephemeral resource such as wrack should have some dispersive capability and should regularly travel across the beach face to locate suitable habitat. In California (US), several thousand talitrid amphipods, *Megalorchestia* spp., were introduced onto a beach where vehicles had recently been excluded but these amphipods were no longer found (Schooler *et al.* 2009). These authors were able to show, with the aid of sentinel (i.e. defaunated) wrack clumps placed along the shore at regular intervals, that these amphipods were able to disperse more than 200m along the beach (Schooler *et al.* 2009). Thus it seems likely that individuals belonging to the wrack-associated macrofaunal community are highly motile, and are able to (and likely do) travel great distances along the length of a beach in search of suitable wrack accumulations.

In doing this, some or many individuals may move into open-to-vehicle sections on beaches and, while there, would be subjected to vehicle impacts. This mobility could then result in negative impacts on macrofaunal communities outside the area of direct vehicle disturbance, possibly via ecosystem flow-on effects (e.g. disruption of food chains or reduced habitat quality), increased metabolic costs of habitat disruption (Schlacher & Thompson 2008), sub-lethal effects of vehicles (Sheppard *et al.* 2009), or by the large-scale spatial effect of populations in flux (i.e. movements of animals in and out of closure areas and so ‘exporting’ vehicle impacts back into closures), as discussed above.

In any case, the spatial extent of the closures investigated here may be too small to encapsulate whole meta-populations, and potential impacts of vehicles on individuals moving outside of closures may have significant implications for the population as a whole (i.e. reduced abundances).

On the other hand, meiofaunal communities do not appear to be affected by vehicles in the same way as the macrofauna. Closure sections on open beaches seem to be sufficiently large to encapsulate meiofaunal communities, and meiofaunal communities are found on open sections. If meiofaunal communities are negatively impacted by vehicles, such an effect could be missed using the study design in Chapter 6 of this thesis if these populations are able to recover from such disturbances rapidly. Meiofaunal communities are known to show rapid recovery (i.e. on a tidal cycle) from short-term physical disturbances (Sherman & Coull 1980; Gheskiere *et al.* 2006). However, vehicle traffic on the beaches studied in this thesis can be considered a press disturbance, rather than a one-off pulse-type event.

Alternatively, it may be that meiofaunal organisms are resilient to the effects of vehicles. Off-road vehicle traffic was only found to have a detectable effect (i.e. above temporal and spatial variation in populations) on meiofaunal copepods in one brief study from New South Wales, Australia (Bell 2005). Meiofaunal communities on Adelaide’s southern beaches were dominated in terms of both abundance and species richness by nematodes (Chapter 6). Whether the application of vehicle traffic does have immediate and/or lasting negative effects on individual taxa or on entire meiofaunal communities remains to be further investigated.

If meiofaunal communities are negatively affected by vehicles, populations within closure sections on open beaches appear to be protected. Thus, unlike the macrofauna, populations of meiofaunal organisms and the resources they require may be spatially constrained within closure sections, thus offering these organisms a degree of ‘protection’ from vehicles. Meiofauna are direct developers (i.e. disperse-less) and are not likely to move great distances unless transported with sediments by the swash, thus the degree of exchange and movement among meiofaunal populations on sandy beaches is likely to be low. Thus the spatial extent of closures on both

Aldinga and Moana Bays may be large enough to sufficiently capture populations of meiofaunal species and thus isolate these organisms from the impact of vehicles.

Few sandy-beach studies have included sampling of both the meio- and macrofaunal communities in their design (e.g. Koop & Griffiths 1982; McLachlan *et al*. 1984; Heymans & McLachlan 1996; Papageorgiou *et al.* 2007; Harriague *et al.* 2008) and, to my knowledge, only one other study has contrasted the different responses of these two groups of beach fauna to any anthropogenic impact, specifically responses to beach cleaning following an oil spill (Bodin & Lemoal 1982). These authors found that although both size-groups were negatively affected by beach cleaning chemicals only the larger macrofauna were also affected by mechanical ploughing (Bodin & Lemoal 1982). Thus, the inclusion of both the macrofaunal and meiofaunal components in this thesis is not only unusual but has helped to identify potential mechanisms for disturbance to macrofaunal communities that are seemingly isolated from vehicle impacts.

Timeframes for population recovery after vehicle exclusion

The results of Chapter 5 indicate that the timeframe for macrofaunal population recovery after vehicle exclusion from a previously-open section of beach may be greater than 15 years (i.e. the time-period of closures at Moana Bay, where only a partial recovery, at best, was observed), if these populations are ever able to recover at all. There are several additional factors that may limit the recovery of these populations aside from the size of vehicle closures on these beaches (discussed above). Firstly, these beaches are all semi-urban, often with developed back-shores and dunes (e.g. Moana North is backed by a seawall and car park built on top of the dunes), and development of the backshore may impact macrofaunal populations of intertidal beaches (McLachlan & Brown 2006; Lucrezi *et al.* 2009). Secondly, regardless of vehicles, these beaches are still highly popular as pedestrian beaches (see Chapter 2), and some macrofaunal species may be trampled by pedestrians (Moffett *et al.* 1998; Colombini *et al.* 2003; Veloso *et al.* 2006; Ugolini *et al.* 2008; Lucrezi *et al.* 2009). Finally, macrofauna may not be able to recolonise these beach sections, due to poor dispersive capacity of recruits (i.e. especially species are direct developers, approximately 72% of species and 96% of macrofauna collected on study beaches), lack of suitable habitat or food for recruits, or due to post-colonisation effects, such as trampling. Although understanding the reasons for these depauperate macrofaunal communities across disturbed beaches (i.e. vehicles, coastal development, tourism, or a combination of factors) is an important step towards managing these beaches to preserve their ecological function, research must also be done into potential restoration actions for macrofaunal populations that appear to be unable to recover after disturbance has ended (Dugan *et al.* 2009).

Variability inherent in natural systems and the importance of sampling design

Beaches are highly dynamic physical systems that vary greatly in time and space (Komar 1976). The inconsistencies among some results in this thesis (i.e. see above) have highlighted the importance of undertaking large-scale, long-term studies when quantifying anthropogenic impacts in such highly variable environments. Investigations of anthropogenic impacts, such as the use of vehicles on beaches, pollution or from some other human activity (e.g. coastal development, beach nourishment, coastal armouring), must be unconfounded by small-scale spatial and/or temporal variation. The large-scale sampling approach of this study, incorporating multiple spatial (e.g. cover-types and beaches; Chapter 5) and temporal (i.e. seasons and years) scales, has allowed detection of this background variation, and isolation of this variation from the human effect of interest, that is vehicle use on these beaches.

Replication within levels of a factor is essential in any study (Hurlbert 1984; Underwood 1997) but especially for studies in highly-variable and unpredictable habitats such as beaches. Often, studies on beaches lack replication within levels of the factor/s of interest; for example, a recent study comparing the reproductive dynamics of *Donax hanleyanus* across beach morphotypes in Argentina (Herrmann *et al.* 2010) included only one beach of each of the Reflective, Intermediate and Dissipative morphotypes, with these three beaches also occurring along a continuous stretch of coast. Hence, the effects of beach morphotype focussed upon in Herrmann *et al.* (2010) cannot be separated from latitudinal effects or spatial variation along a coastline (or any other less-obvious differences among the three beaches). My study has included replicate beaches within levels of the factor Type (i.e. two each of open and closed beaches) and also replicate Bays with multiple vehicle-access Types (i.e. Aldinga and Moana Bays). This design has shown that there are some important differences between beaches of the same type (e.g. relatively high dissimilarity of macrofaunal communities among closed beaches; see Table 5.4). The inclusion of replicate beaches of the same morphotype (i.e. all the Low-Tide Terrace Intermediate type) among vehicle-access Type levels has also allowed the isolation of this spatial variation among beaches and thus avoided mistakenly interpreting this natural variation that exists among the beaches sampled as some effect of vehicles.

This study was also designed so that sampling occasions were based around both vehicle activity on the beaches (see Chapter 2) and known seasonal shifts in beach morphology so as to incorporate this potential temporal variation (Komar 1976) without misinterpreting it as an effect of vehicles. The detection and subsequent isolation of natural temporal (and spatial) variation, especially on a seasonal scale, is arguably more important on beaches of Intermediate morphotypes, because these are known to be more unstable in space and time than either the Reflective or Dissipative extremes (Short & Wright 1983). Indeed, the results of Chapter 3 do indicate that the physical nature (i.e. profiles, sediment characteristics, total physical environment) of the beaches in the study region is highly variable throughout time, both among seasons within years and among years. However, the effects of highly unstable (i.e. through time) Intermediate beach morphotypes on biotic communities have not been studied, nor the effects of anthropogenic impacts on top of this physical variability.

This study has used management actions on these beaches controlling vehicle access (i.e. beach or section closures) to create a quasi-experimental design that was capable of isolating vehicle impacts on beaches. Untangling of vehicle impacts from spatial and temporal variation has been achieved in this thesis with the use of a large-scale (i.e. multiple sites of various vehicle access types) sampling design. This design incorporated spatial variation (i.e. among beaches) and multiple temporal scales (i.e. among seasons and years). Isolating vehicle effects has also been achieved by looking at multiple aspects of this issue, from fine-scale measurements (e.g. displacement, Chapter 4) through to macro-scale observations (i.e. Chapter 3), and by including both physical (Chapters 2-4) and biological (Chapters 5-6) aspects of beaches that may be affected.

Key areas for further research

There are a number of aspects of vehicle disturbance that are not well understood, relating to impacts on macrofauna, ecosystem links, processes and function that should be the focus of further research. This is especially important if we are to effectively manage vehicle access for the purpose of preserving, maintaining or restoring ecological function of the beach. I have already highlighted two key areas for potential further research. Firstly, the existence of depauperate macrofaunal communities across beaches with vehicles, regardless of vehicle closure regimes (i.e. permanent versus seasonal closures), suggests that the spatial extent of closures on these beaches is insufficient to encapsulate and protect macrofaunal populations and the spatial extent of vehicle disturbance, both along the beach face and in linked environments should be quantified with the mechanisms of disturbance identified. Secondly, if beaches are to be managed for vehicle impacts with the goal of maintaining or restoring ecological function, then restoration efforts may also be needed, and methods for recolonising defaunated beaches may need to be developed (Dugan *et al.* 2009).

1. Exploring spatial scale of vehicle impacts on beaches and linked habitats

Effects of vehicles on macrofaunal organisms need to move towards a focus on the mechanisms responsible for associated reductions in population abundance (Steiner & Leatherman 1981; Foster-Smith *et al.* 2007; Schlacher *et al.* 2007b) and overall community abundance (Schlacher *et al.* 2008c; Chapter 5, this thesis). Beaches are also linked to near-shore marine (e.g. Soares *et al.* 1997) and terrestrial habitats (e.g. Schlacher & Connolly 2009) and vehicle effects may extend beyond the intertidal beach-face. Thus, it seems important to quantify the spatial extent of vehicle disturbance on both beaches and linked ecosystems, which may be larger than the area of actual vehicle use. In conjunction with this, we also need to improve our understanding of these links between beaches and other habitats, and potential mechanisms for vehicle impacts upon these.

In particular, areas for further study should include vehicle effects on the quality of wrack habitat (i.e. as both food and shelter) and on the utilisation, colonisation and decomposition of wrack by macrofauna on beaches. Another area for further investigation relates to how macrofaunal organisms move along beaches (i.e. are they redistributed with wrack by the swash at high-tide or do they traverse the beach-face and select wrack habitat?) and how often they move (e.g. rates of movement and/or exchange of macrofauna in and out of closure sections on open beaches). The effects of surface roughness and wide-spread rutting of the high-shore by vehicle tyres on macrofaunal movements could be investigated experimentally by measuring rates of travel across uneven ground, in the same way as has been done for turtle hatchlings by Hosier *et al.* (1981).

Another possibility would be to use laboratory experiments to investigate burrowing ability (and burrow stability) for key beach species under a range of values for sediment compaction and moisture contents experienced by these species on beaches with vehicles, as has been done to investigate the effects of sand-grain particle size on borrowing in beach mysids (Nel *et al.* 1999) and bivalves (Nel *et al.* 2001).

The method for translocation and then monitoring of the dispersion of macrofauna on defaunated vehicle beaches developed by Schooler and others (2009) could now be applied as an experimental tool. By placing macrofaunal species into previously suitable habitat and monitoring their survival it would be possible to determine whether the absence of macrofauna is due to a restricted dispersive capacity of macrofaunal organisms (i.e. the translocated population successfully establishes itself on a vehicle beach) or impacts occurring post settlement (i.e. to clarify some issues raised in Chapter 5). If the latter (i.e. populations are not able to establish themselves in the long term), then perhaps the spatial extent of closures needs to be larger if the restoration of ecological function is a management priority on these beaches.

Finally, fully terrestrial species, such as insects and spiders, are often absent from beaches with vehicle access (Schlacher *et al*. 2008c; Chapter 5, this thesis). Vehicle use in dune systems has been shown to negatively impact beetles (Van Dam & Van Dam 2008) and arthropods (including beetles) and also lizards and mammals (Luckenbach & Bury 1983). The absence of dune invertebrates on beaches with vehicles may be attributed to either an absence of these species from the dunes also (i.e. do vehicle impacts also extend up into terrestrial habitats that are not subject to vehicle disturbance otherwise?) or these species may present in the dunes but are unable to negotiate the highly disturbed and rutted high-shore zone.

2. Restoration of disturbed beaches

Recovery of macrofaunal populations on beaches previously subject to vehicle disturbance may be slow (i.e. there was no evidence for recovery even after at least 15 years of vehicle exclusion at Moana Bay; Chapter 5, this thesis) and, if provision of food for shorebirds is a priority, then some restoration actions may be needed (Dugan *et al.* 2009). Translocation of talitrid amphipods onto beaches that have been defaunated by vehicle disturbance has been successful as a novel technique (Schooler *et al.* 2009). This method may be developed to re-establish entire macrofaunal communities based on either historical data, where this is available, or some local reference community (e.g. those communities observed on nearby beaches closed to vehicles [Maslin & Port Willunga] in southern Adelaide). This could be as simple as placing wrack containing macrofauna on Aldinga and Moana Beaches, sourced from nearby closed beaches (i.e. Maslin and Port Willunga).

Additionally, the findings of the research suggested above may be used to develop further management or restorative actions that may aid in the recovery of macrofaunal populations on beaches with vehicles. For example, if populations of terrestrial species, such as beetles, are present in the dunes but are prevented from accessing suitable habitat on the intertidal beach due to heavily rutted high-shore beach topography, then restricting driving to the mid- and low-shore zones may allow high-shore topography to return to normal and these species to access the intertidal beach.

Management of this activity on Adelaide's southern metropolitan beaches

The impacts of vehicles on sediments and profiles of the beaches in southern metropolitan Adelaide appear to be minimal, with trends for a general degradation of the physical environment of the beach rather than destruction of the entire physical system (Chapter 3-4). Sediment disruption and downslope displacement effects were only notable in the high shore (Chapter 4). Thus this negative impact on the study beaches could potentially be completely eliminated by restricting driving to the mid- and low-shore zones of the beach. This action has previously been suggested by Anders and Leatherman (1987) for the Fire Island (USA) beach on which they studied sediment displacement and disruption by vehicles.

Regardless of whether vehicles are responsible for the overall depauperate nature of macrofaunal communities on beaches open to vehicle use or not, the apparent loss of this group of organisms from the beach ecosystem is concerning. Wrack-associated macrofauna are one group of organisms that feed on the detached macrophytes deposited on the beach-face, and thus form a link in beach food-chains between this input of coarse organic material and higher level consumers, such as birds and near-shore fish (Kirkman & Kendrick 1997; Colombini & Chelazzi 2003; Heck *et al.* 2008). The loss of this group of organisms has significant implications for populations of bird species that feed and nest on these beaches, including the locally vulnerable *Thinornis rubricollis* (Hooded Plover) (Baker-Gabb & Weston 2006; Ellis 2006; Stephens 2009). Vehicles have been identified as a major threat to *T. rubricollis* populations in South Australia (Baker-Gabb & Weston 2006), with fewer *T. rubricollis* sightings on beaches with higher vehicle use (Stephens 2004).

Just prior to completion of this thesis, the local council (Onkaparinga City Council) responsible for managing these beaches voted to continue the current vehicle restrictions on Aldinga Bay Beach (restrictions in place at Moana Bay had not been under debate). The purpose of these restrictions is not primarily to preserve ecological function but rather to provide safe, vehicle-free areas on this heavily-used beach, especially for small children at risk of being hit by passing cars. If preserving or restoring ecological function does at some point in the future become a priority, I recommend that the research suggested above regarding the spatial extent of vehicle impacts and possible restoration efforts be conducted. An understanding of these aspects would allow the establishment of closure sections that are ecologically meaningful and functional.

Conclusions

The overall aim of this thesis (see Figure 1.5), to assess the impacts of vehicles on the physical and biological components of beaches in southern metropolitan Adelaide, and to determine which aspects were prominent locally, has been achieved (Table 7.1). This thesis has shown the importance of investigating potential negative impacts of an activity, vehicle use on beaches, only roughly known from the scientific literature, in a local situation. This is especially important where the local situation is very different from systems previously studied for such effects, as is the case for beaches in southern metropolitan Adelaide, which experience a different type and degree of vehicle usage from any other beaches studied for vehicle impacts previously.

The next steps forward to further improve our understanding of vehicle impacts on intertidal beaches must include a movement away from studies of individual species susceptibility to vehicle crushing or other direct impacts and towards an understanding of aspects that will aid the effective management of this activity on beaches. Specifically, I believe it is essential that we determine the dispersive capacities of key species (e.g. Schooler *et al.* 2009) by investigating the mobility of populations and communities along and across beaches, determine vehicle impacts on ecological linkages (Schlacher *et al.* 2008c) such as food chains and key functions or ecological processes (e.g. decomposition of wrack), and define the realised area of impact of this activity, which may extend beyond the area of actual impact. This last point is especially important if we are to create closure sections on beaches otherwise open to vehicles in order to provide effective refugia to macrofauna. Via these efforts, we may be able to contribute towards better management of this activity on beaches.